WOODFIBRE LNG PROJECT
VESSEL WAKE ASSESSMENT

Prepared for:

Woodfibre LNG

Woodfibre LNG Ltd.

Prepared by:

moffatt & nichol

777 W. Broadway, Suite 301
Howe Sound, BC, V5Z 4J7

Woodfibre LNG Project FEED
Vessel Wake Assessment
WOODFIBRE LNG LIMITED

M&N Project No. 8359-16

Prepared by:

MOFFATT & NICHOL

[Original hardcopy signed by C-F Tsai and M. Jorgensen]

Cheng-Feng Tsai, P.E.
Mads Jorgensen, P.E.

Reviewed by:

MOFFATT & NICHOL

[Original hardcopy signed by R. Byres]

Ron Byres, P.Eng.
Project Director

Revision	Purpose of Issue	Date	Author	Reviewed
A	Draft Report	April 23, 2015	CT/MJ	RDB/FS

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ACRONYMS

AIS	Automatic Identification System
BC	British Columbia
CFD	Computational Fluid Dynamics
CHS	Canadian Hydrographic Service
DFO	Fisheries and Oceans Canada
EAO	Environmental Assessment Office
FEED	Front End Engineering Design
FLNG	Floating Liquefied Natural Gas
FSO	Floating Storage and Offloading
LBP	Length Between Perpendiculars
LNG	Liquefied Natural Gas
LNGC	Liquefied Natural Gas Carrier
LOA	Length Overall
M&N	Moffatt & Nichol

RANS	Reynolds Averaged Navier-Stokes (equation; computational fluid dynamics).
TBP	Tonne Bollard Pull
WLNG	Woodfibre LNG Limited

GLOSSARY OF NAUTICAL TERMS

Aft	Towards or at the back part of a ship.
Astern	Behind or towards the back part of a ship.
Bathymetry	Referring to the water's depth relative to sea level, i.e. submarine topography.
Beam	The extreme width of a ship at the widest part.
Bollard pull	A conventional measure of the pulling (or towing) power of a tug measured in tonnes, abbreviated as TBP.
Bow	The forward part of a ship.
Celerity	The speed of propagation of a surface wave.
Deadweight Tonnage	Deadweight tonnage is a measure of how much weight a ship can safely carry, and is the sum of the weights of cargo, fuel, fresh water, ballast water, provisions, passengers, and crew.
Displacement	Displacement is the weight of water that a ship displaces when it is floating, which in turn is the weight of a ship (and its contents).
Draft	The depth of water a ship draws especially when loaded.
Gross Tonnage	Gross tonnage is a unitless index related to a ship's overall internal volume, calculated based on the moulded volume of all enclosed spaces of the ship, and is used to determine things such as a ship's manning regulations, safety rules, registration fees, and port dues, whereas the older gross register tonnage is a measure of the volume of certain enclosed spaces.
Knots	A measure of a ship's speed (one knot equals one nautical mile per hour or 1.852 kph).
Portside	Referring to the left side of a ship perceived by a person on board facing the front of the ship.
Starboard	Referring to the right side of a ship perceived by a person on board facing the front of the ship.
Stern	The back part of a ship.
Vessel	Nautical term for any craft designed for transportation on water, such as a ship or boat.
Wake	The waves or track left by a vessel or other object moving through water.

Source: http://en.wikipedia.org/wiki/Glossary_of_nautical_terms.

EXECUTIVE SUMMARY

Woodfibre LNG Limited (WLNG) is proposing the development and operation of a liquefied natural gas (LNG) production facility with marine storage and off-loading (project) near Squamish, British Columbia. Moffatt & Nichol (M&N) is providing the Front End Engineering Design (FEED) for the terminal marine facilities, which is designed to accommodate LNG Carriers (LNGC) up to 174,000 m^3 capacity.

In the initial stages of the FEED, M&N developed an initial assessment of vessel wakes attributed to LNGC transits through Howe Sound. This study focused on wake formation as a function of speed and distance from the LNGC. This information was included in Appendix 7.3-2 of the Application for an Environmental Assessment Certificate (Application) for the project.

The Application is currently under review and a request has been received to provide additional information regarding vessel wakes associated with the Project and their potential for environmental effects. This report addresses wake effects associated with transits of LNGCs, escort tugs, worker ferry, and existing BC ferries, comparing these to natural waves under typical and severe conditions and assesses the potential effects on different shoreline types and infrastructure within Howe Sound.

The present study examines wake wash associated with passage of LNGCs, escort tugs, worker ferries, and existing BC ferries.

FINDINGS AND CONCLUSIONS

Findings of a preliminary wake analysis support the following conclusions:

- Based on the low speed at which LNGCs will travel in Howe Sound in relation to their size, vessel wakes are expected to be very small, essentially at the verge of wake formation. Several field studies by others have confirmed this finding.
- The tugs operate at higher velocities relative to their size and therefore more readily produce a wake.
- The wave period and wave lengths for vessels associated with the Woodfibre LNG Project are in the range of typical wind-generated waves, and will behave much the same as natural waves of the same size when they reach the shore.
- Wakes generated by the existing ferries in Howe Sound have somewhat longer wave periods and wave lengths compared to project vessels and natural conditions, and therefore are relatively more noticeable when compared to natural ambient conditions.

- Many people remember the notable wakes generated by the PacifiCat fast ferries. The fast ferries produced wakes with wave periods of around 9 seconds, which is comparable to ocean swell waves and would be much more noticeable against the background ambient conditions.

The study arrives at the following conclusions:

1. Wakes from project vessels are found to be comparable to naturally occurring waves within Howe Sound.

2. Project related vessel traffic volumes will be small relative to existing traffic levels and project wakes will not appreciably increase the existing vessel wake environment.

3. Wakes from project vessels transiting to the Woodfibre site are projected to be smaller than the wakes generated by the existing BC Ferries because project vessels will transit at lower speeds and will travel as far removed from shore as practicable.

4. Wakes from vessels transiting to the Woodfibre site will be less than wakes generated by existing vessels transiting to Squamish Terminals, because project vessels will transit at substantially lower speed.

5. To the extent that the present study is accurate, it is not envisaged that wake waves would heighten exposure of the public, contribute to shoreline erosion, or have any appreciable effect on existing infrastructure within Howe Sound.

6. It is concluded that no additional wake mitigation measures are necessary for project-related vessel traffic beyond those considered within this study.

1. INTRODUCTION

1.1 PROJECT BACKGROUND

Woodfibre LNG Limited (WLNG) is proposing the development and operation of a liquefied natural gas (LNG) production facility with marine storage and off-loading (project) near Squamish, British Columbia. WLNG has engaged Moffatt & Nichol (M&N) to provide the Front End Engineering Design (FEED) for the floating storage and offloading unit (FSO) Berth at the marine terminal, which consists of a loading platform and berthing and mooring for the following:

- FSO – Floating Storage and Offloading Unit, consisting of two 125,000 m^3 LNG carriers combined, permanently moored at berth; and,
- LNGC – Liquefied Natural Gas Carrier, 174,000 m^3 LNG carrier, moored alongside the FSO unit.

In the initial stages of the FEED, M&N developed an initial assessment of vessel wakes attributed to LNGC transits through Howe Sound. This study focused on wake formation as a function of speed and distance from the LNGC. This information was included in Appendix 7.3-2 of the Application for an Environmental Assessment Certificate (Application) for the project.

The Application is currently under review and a request has been received to provide additional information regarding vessel wakes associated with the Project and their potential for environmental effects. This study addresses wake effects associated with transits of LNGCs, escort tugs, worker ferry, and existing BC ferries, comparing these to natural waves under typical and severe conditions. Additional information is also provided regarding how wake wash would impact different shoreline types and infrastructure within Howe Sound.

1.2 SCOPE

The scope of study is based on a series of questions by the Environmental Assessment Office (EAO) submitted to Woodfibre on March 24, 2015 as follows:

Part A)

> *Submit a wake assessment in consideration of worst-case scenarios involving combined wake effects resulting from:*
>
> *i)* *an LNG carrier accompanied by 3 escort tugs;*
>
> *ii)* *an LNG carrier with escort tugs and a BC Ferry; and*
>
> *iii)* *the largest worker ferry.*

> *Scenarios should be assessed under both typical and severe weather conditions and at a range of travelling speeds and vessel configurations.*
>
> *The assessment should provide a description of predicted combined wake effects compared to natural waves under each scenario.*
>
> *Based on the results above, describe whether this would change the mitigations or conclusions of residual adverse effects from the Application.*

Part B)

> *Explain how the wake wash from the scenarios described above would impact different shoreline types and infrastructure occurring within Howe Sound.*
>
> *Describe key mitigations and characterize potential residual effects from combined wake wash.*

2. SITE DESCRIPTION

2.1 LOCATION

The present study focuses on the LNG carrier's route after entering Howe Sound, an approximately 40 kilometers deep fjord off the Strait of Georgia. General descriptions about Howe Sound are excerpted from Fisheries and Oceans Canada (DFO) *Sailing Directions*, "Howe Sound is entered between Point Atkinson (49°20'N, 123°16'W) and Gower Point, 11 miles WNW. Several islands divide the entrance into four main channels named, from east to west, Queen Charlotte Channel, Collingwood Channel, Barfleur Passage and Shoal Channel. Howe Sound offers few small craft anchorages due to great depths and lack of protected bays. The sound is almost entirely hemmed in by rugged, precipitous mountains rising abruptly from the water's edge" *(DFO, 2012)*.

Figure 2-1 shows the map of Howe Sound and some locations of interest, overlapped with the existing BC ferry routes and proposed Woodfibre LNG traffic routes (LNG carrier and worker ferry).

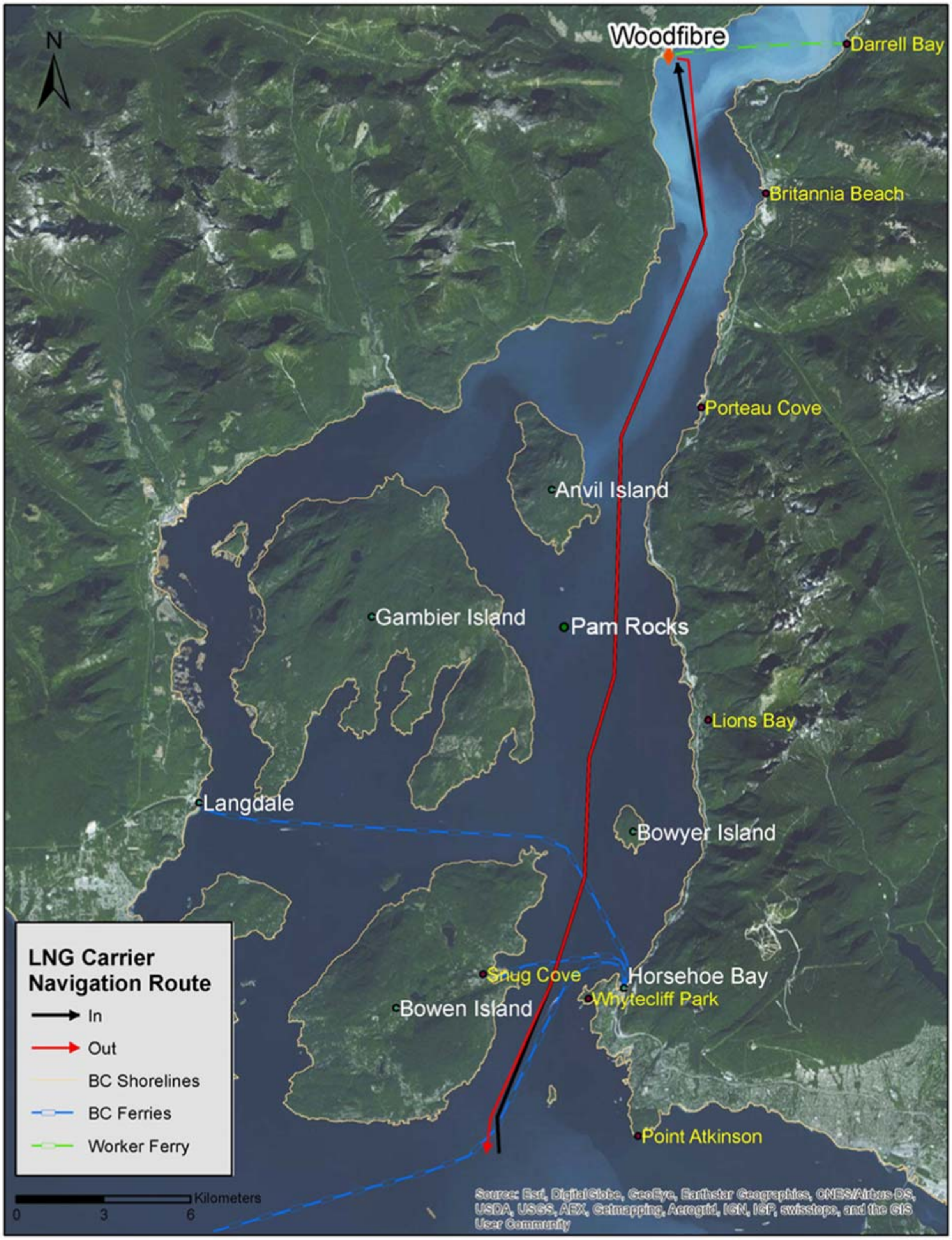


Figure 2-1: Map of LNGC and ferry routes in relation to geographical areas and site locations within Howe Sound.

2.2 METOCEAN CONDITIONS

Metocean conditions for Howe Sound are described in the subsequent sections. Detailed analyses for the metocean conditions refer to Moffatt & Nichol *Metocean Report (2015)*.

2.2.1 Bathymetry

Water depths along navigation routes within Howe Sound typically range from around 200-250 meters relative to Chart Datum.

2.2.2 Water levels

Table 2-1 summarizes the tidal datums at Point Atkinson, Gibsons, and Squamish from the CHS Nautical Chart 3526 and implies that there is little spatial variation in water levels within Howe Sound.

Table 2-1: Tidal Datums.

Location	Elevation Above Chart Datum (m, CD)				
	Large Tide		Mean Tide		Mean Water Level
	HHW	LLW	HHW	LLW	
Point Atkinson	5.1	0.0	4.4	1.2	3.1
Gibsons	5.2	0.0	4.5	1.2	3.2
Squamish	5.1	0.0	4.5	1.2	3.1

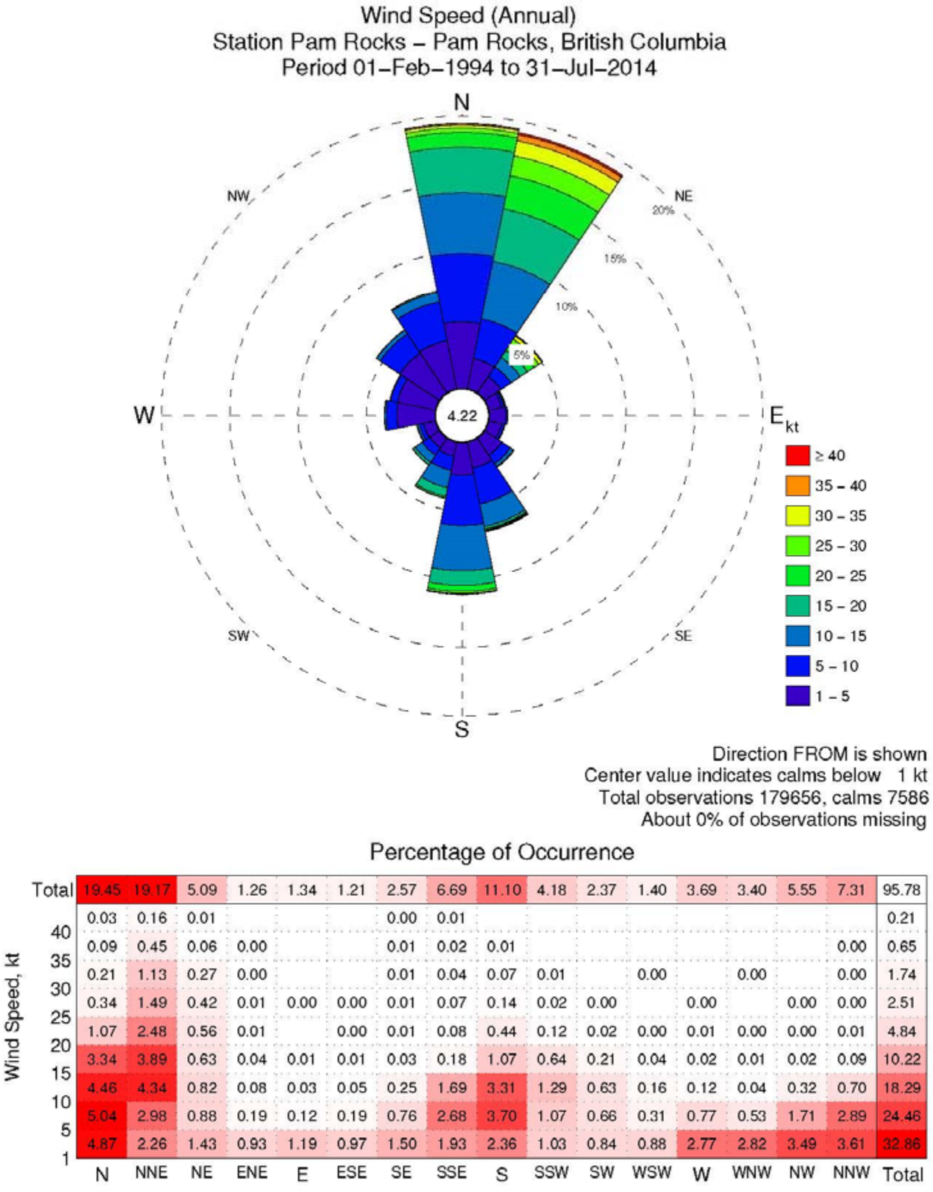
Extreme high and low water levels were calculated based on the observed hourly water levels at Point Atkinson (Table 2-2).

Table 2-2: Extreme Water Levels.

Return Period (years)	High Water Levels (m, CD)	Low Water Levels (m, CD)
1	5.24	-0.02
5	5.42	-0.13
10	5.47	-0.16
25	5.53	-0.20
50	5.57	-0.23
100	5.61	-0.25

2.2.3 Winds

Pam Rocks are located in the middle of Howe Sound and are in close vicinity to the navigation routes. Therefore, it is considered generally representative of the wind climate experienced while the LNG carrier is transiting within Howe Sound. Figure 2-2 illustrates the annual wind rose at Pam Rocks.



Direction FROM is shown
Center value indicates calms below 1 kt
Total observations 179656, calms 7586
About 0% of observations missing

Percentage of Occurrence

Wind Speed, kt	N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW	Total
Total	19.45	19.17	5.09	1.26	1.34	1.21	2.57	6.69	11.10	4.18	2.37	1.40	3.69	3.40	5.55	7.31	95.78
≥ 40	0.03	0.16	0.01				0.00	0.01									0.21
35 – 40	0.09	0.45	0.06	0.00			0.01	0.02	0.01							0.00	0.65
30 – 35	0.21	1.13	0.27	0.00			0.01	0.04	0.07	0.01		0.00		0.00		0.00	1.74
25 – 30	0.34	1.49	0.42	0.01	0.00	0.00	0.01	0.07	0.14	0.02	0.00		0.00		0.00	0.00	2.51
20 – 25	1.07	2.48	0.56	0.01		0.00	0.01	0.08	0.44	0.12	0.02	0.00	0.01	0.00	0.00	0.01	4.84
15 – 20	3.34	3.89	0.63	0.04	0.01	0.01	0.03	0.18	1.07	0.64	0.21	0.04	0.02	0.01	0.02	0.09	10.22
10 – 15	4.46	4.34	0.82	0.08	0.03	0.05	0.25	1.69	3.31	1.29	0.63	0.16	0.12	0.04	0.32	0.70	18.29
5 – 10	5.04	2.98	0.88	0.19	0.12	0.19	0.76	2.68	3.70	1.07	0.66	0.31	0.77	0.53	1.71	2.89	24.46
1 – 5	4.87	2.26	1.43	0.93	1.19	0.97	1.50	1.93	2.36	1.03	0.84	0.88	2.77	2.82	3.49	3.61	32.86

Figure 2-2: Annual Wind Rose at Pam Rocks.

Hourly wind data at Pam Rocks between February 1994 and July 2014 were analyzed. Table 2-3 summarizes the wind statistics. The wind speed is reported in knots due to its common use in the marine practice. One knot is equivalent to one nautical mile per hour, or 1.852 km/hour.

Table 2-3: Wind Statistics at Pam Rocks.

Wind Speed in knots (2-min average)				100-Year Wind Speed in knots		Prevailing Wind Direction (From)
50th Percentile	75th Percentile	95th Percentile	Max	Expected Value	95% Non-Exceedance	
7.0	13.0	25.9	62.1	57.6	61.3	N-NNE

2.2.4 Waves

Howe Sound is considered a "fetch limited" wave environment. Low frequency swell waves from the open Pacific Ocean are essentially completely attenuated by the time they reach Howe Sound. Locally-generated wind waves are therefore the only natural sea waves of any consequence.

Historical wave measurements at Pam Rocks (Environment Canada station c46182) between September 1989 and November 1991 were available through DFO (http://www.isdm-gdsi.gc.ca). A good correlation between the observed significant wave height and wind speed was found (Figure 2-3). Therefore, the wave environment within Howe Sound is verified to be dominated by local wind-generated seas.

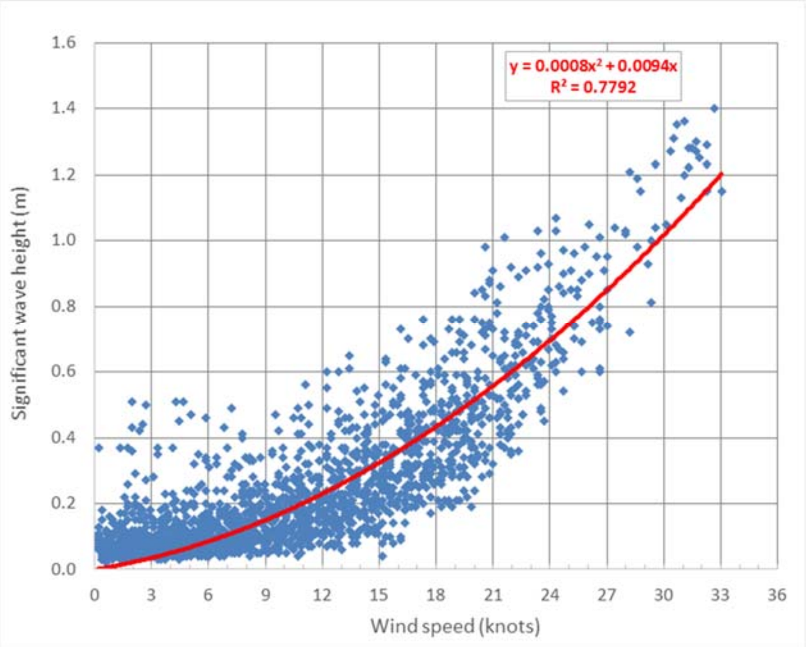


Figure 2-3: Correlation between Significant Wave Height and Wind Speed at Pam Rocks.

Figure 2-4 and Figure 2-5 illustrate wind-generated waves for a typical summer breeze. These wind waves are based on a MIKE-21 hydrodynamic numerical model for Howe Sound as described in the Metocean Analysis *(M&N, 2015).* For the current study, a summer breeze is defined as the median wind speed of southerly "inflow" winds during daytime hours (6 A.M. to 6 P.M.) over the months of June through August. A summer breeze was determined to be 9 knots based on the Metocean Analysis *(M&N, 2015)*.

It can be seen that under typical summer sea breeze conditions, the shoreline is expected to experience maximum "significant wave heights"[1] within the range of 0.14 to 0.2 meters with a peak period around 1.5 second. Natural wave heights are frequently larger than this of course, since winds of 10-15 knots or more often prevail. However, for the purposes of assessing the effect of wake waves in relation to natural ambient conditions, it is conservative to consider a gentler wind speed with smaller ambient waves.

---

[1] "Significant wave height" or H_s is a commonly used term to describe the height of a sea state or wave spectrum containing waves of multiple heights. H_s is defined as the average height of the highest one-third of waves in the wave spectrum.

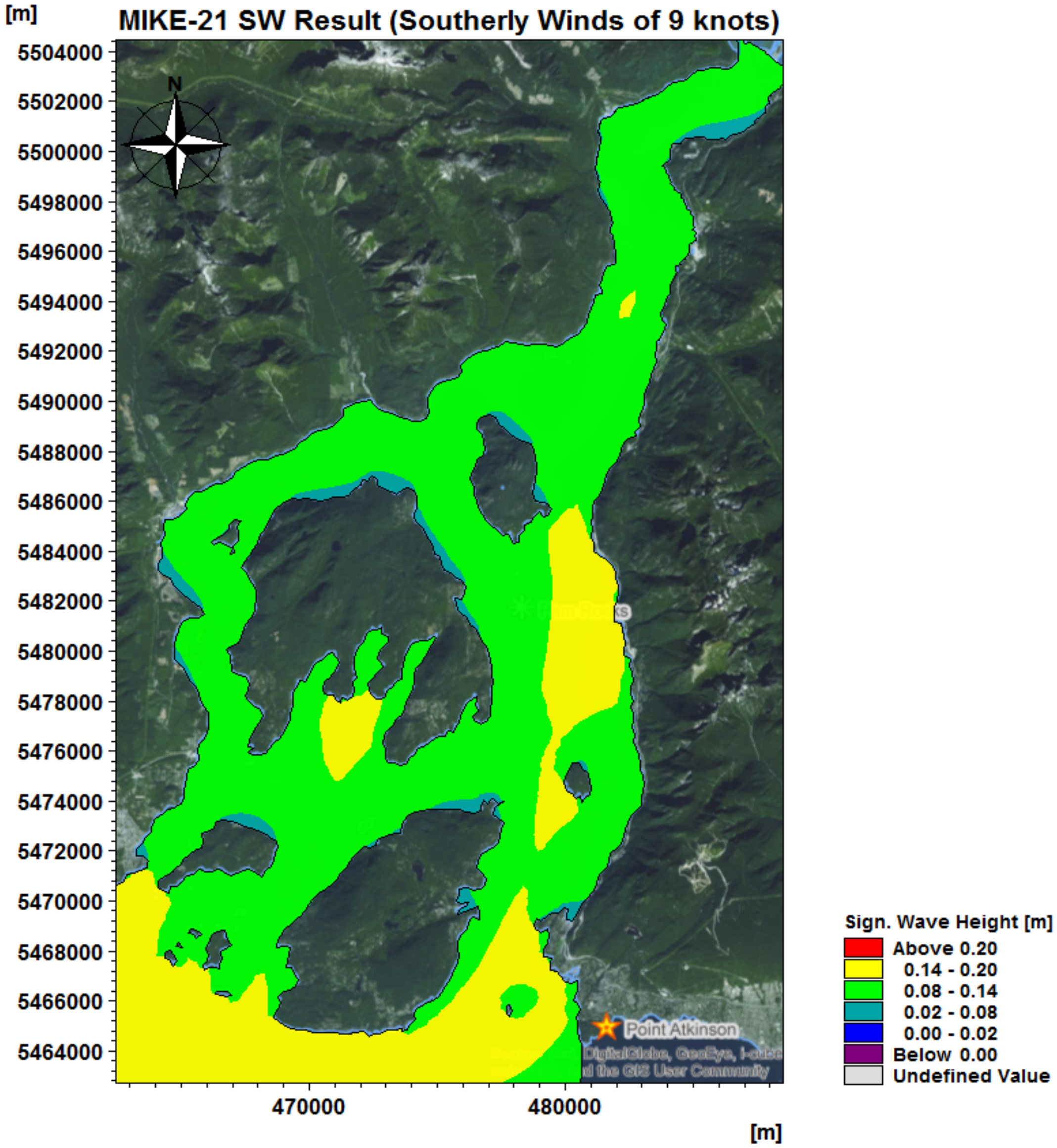


Figure 2-4: MIKE-21 Significant Wave Height for Typical Summer Breeze from Southerly Winds.

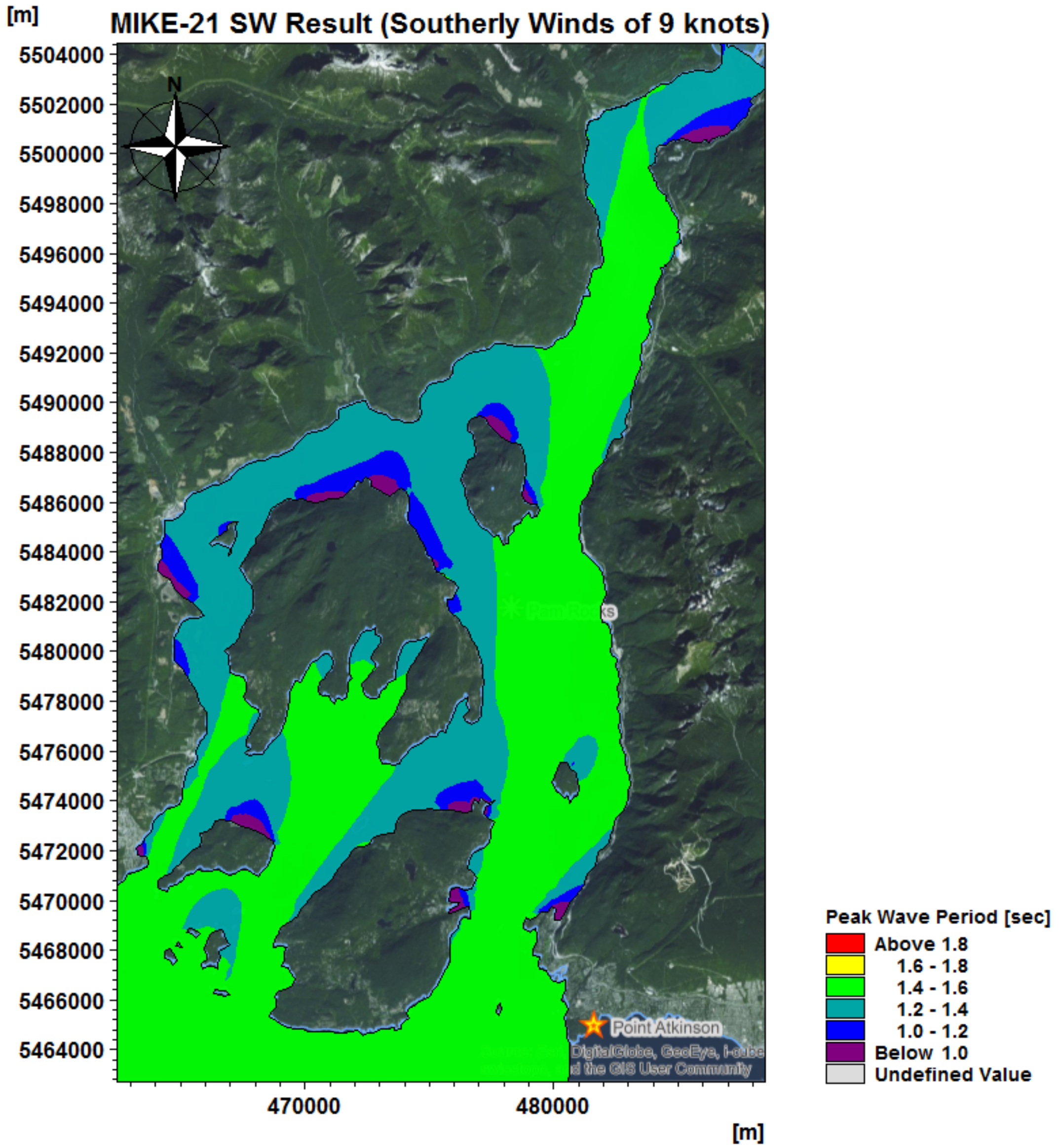


Figure 2-5: MIKE-21 Peak Period for Typical Summer Breeze from Southerly Winds.

2.2.5 Currents

Along the navigation routes (locations see Figure 2-1), information on tidal currents is provided on CHS Nautical Chart 3526. At the entrance to Queen Charlotte Channel, between Passage Island and Bowen Island, the maximum flood and ebb currents are both about 0.5 knots. Between Lions Bay and the Halkett Bay Marine Park on Gambier Island and between Porteau Cove and Anvil Island, the flood currents and ebb currents are estimated to be 1.5 knots and 2 knots respectively. At the entrance into the boundary of the Squamish Harbour, just southwest of the Britannia Beach, the flood currents and ebb currents are estimated to be 1 knot and 1.5 knots respectively.

2.3 NAVIGATION ROUTES

2.3.1 LNGC and Escort Tug Navigation Route

The planned navigation route for LNGCs assumes entry into Howe Sound via the Queen Charlotte Channel (CHS Nautical Chart 3526) between Bowen Island and Point Atkinson, and transit past Bowyer Island and Anvil Island to the Woodfibre site. Inbound and outbound navigation follows practically the same route apart as shown in Figure 2-1.

Anticipated LNGC transits are 80 (one-way) trips per year, i.e. 40 inbound transits and 40 outbound transits.

Pictures of a representative LNG carrier and tug are provided in Figure 2-6. The vessel particulars are summarized in Table 2-4.

INBOUND NAVIGATION PROCEDURE

Transits of LNGC's to the Woodfibre site can be summarized as follows:

- Upon entry into the Juan de Fuca Strait, a pilot boat and escort tug will meet the LNGC at Brotchie Ledge near Victoria, BC.
- Two pilots board and take control of LNGC before entry into the Strait of Georgia.
- Pilotage of the LNGC proceeds up through the Strait of Georgia and into Howe Sound.
- Within Howe Sound, LNG carriers will be accompanied by escort tugs.[2] Preliminary navigation simulations suggest the optimal configuration for escorts is to have two tugs tethered at the stern, with a third escort tug travelling abut 500m ahead. This is the configuration used for this study.
- Upon arrival at Woodfibre, an additional harbour tug will meet the LNGC and assist the escort tugs with final approach and berthing of the LNGC.

---

[2] Escort tugs will also likely be required in the Haro Strait/Boundary Pass section of the route; however, at this time, the escort tug protocol for those areas has not been determined.

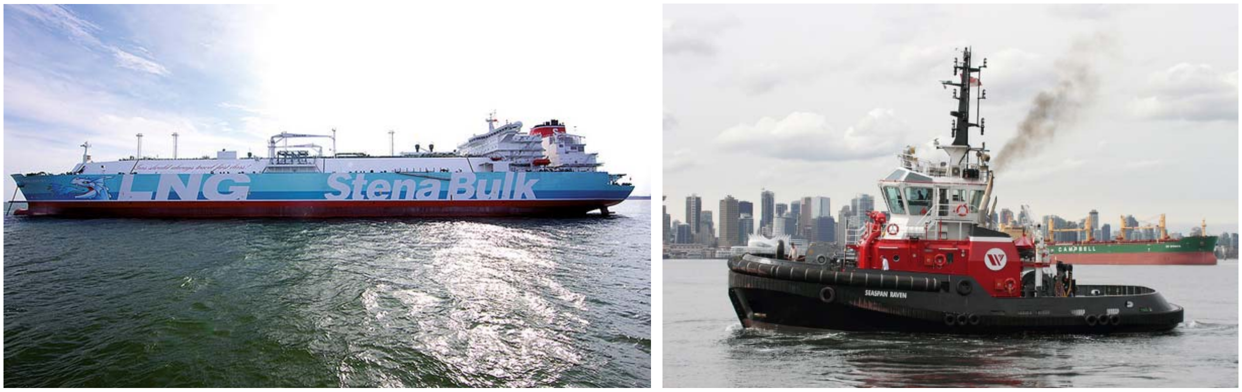


Figure 2-6: LNGC Stena Crystal Sky (left), Tug Seaspan Raven (right). Source: *Flickr (2015)*.

2.3.2 Woodfibre Worker Ferry Route

The planned route for the worker ferry is between Darrell Bay and the Woodfibre site. The vessels considered for ferry service include the Quinsam, Garibaldi II, or a similar vessel (Figure 2-7). Anticipated ferry transits are 6 (one-way) trips per day, i.e. 3 round trips.

Figure 2-7: Quinsam (left), Garibaldi II (right). Source: *BCFerries (2015), MarineTraffic (2015)*.

Particulars of vessels associated with transits to the Woodfibre site are summarized in Table 2-4.

Table 2-4: Particulars of vessels transiting to Woodfibre.

Route	Queen Charlotte Channel to Woodfibre		Darrell Bay to Woodfibre	
Particulars	**LNG Carrier**	**Tugs**	**Worker Ferry**	**Worker Ferry**
Name(s)[3]	Stena Clear Sky	Seaspan Osprey Seaspan Raven	Quinsam	Garibaldi II
Length Overall	298.0 m	28.2 m	86.9 m	31.0 m
Waterline Length	279.0 m	25.9 m	82.5 m	30.5 m

---

[3] Vessel names indicated are representative of largest vessels anticipated.

Route	**Queen Charlotte Channel to Woodfibre**		**Darrell Bay to Woodfibre**	
Particulars	**LNG Carrier**	**Tugs**	**Worker Ferry**	**Worker Ferry**
Beam	45.8 m	12.6 m	21.2 m	12.5 m
Draft	12.92 m	5.39 m	1.8 m	2.0 m
Capacity[4]	174,000 m^3	81 TBP	400 pass	332 pass
Gross Tonnage	109,949	441	1,459	337
Displacement	131,668 tonnes	12 tonnes	1,431 tonnes	306 tonnes
Deadweight Tonnage	96,811 tonnes	132 tonnes	361 tonnes	50 tonnes
Propulsion	44,548 kW	4,698 kW	1,528 kW	470 kW
Service Speed[5]	8-10 knots	8-10 knots	12 knots	10 knots
Maximum Speed	18 knots	13 knots	12 knots	10 knots

2.3.3 Existing Inbound and Outbound Vessel Traffic

Ocean-going vessels inbound and outbound from Squamish report their position, heading, and speed to the Automatic Identification System (AIS) for navigational purposes. Figure 2-8 shows a compilation of vessel transits captured in the AIS data during 2014. Per the chart provided in Appendix A, the average number of commercial vessel transits to the Squamish area is on the order of 1-2 vessels per day. For comparison, LNGCs transiting to Woodfibre are estimated to have a frequency of arrivals of one vessel every 4-5 days.

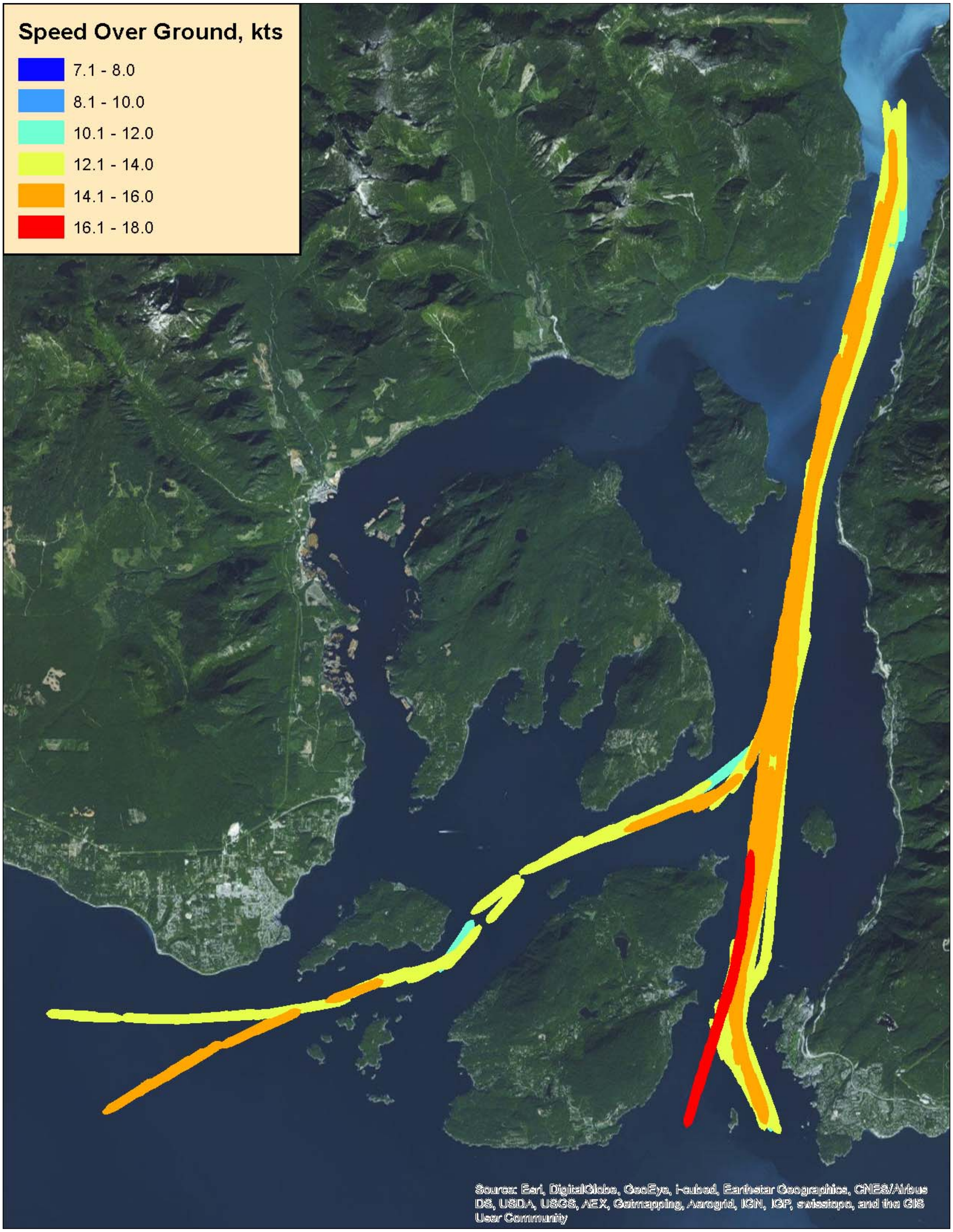
The data show that vessels currently transiting to Squamish navigate along a route similar to that planned for the LNGC transits. Speeds recorded for existing vessel traffic ranges from 12 to 16 knots, with instances of speeds reaching 16-18 knots past Bowen Island.

Figure 2-9 shows example vessel transits to and from Squamish past Oliver's Landing and Porteau Cove where it can be seen that vessels generally navigate in the middle of the sound, but occasionally pass closer to land. Estimated distances to shore range from around 800 m to 1800 m.

---

[4] Note: Cargo capacity (for LNGC), pulling capacity (for tugs), and passenger capacity (for ferry).

[5] Service speed is for vessels within Howe Sound.



Source: Esri, DigitalGlobe, GeoEye, i-cubed, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community

Figure 2-8: Transit speeds captured in AIS data for large commercial vessels transiting to Squamish, BC.

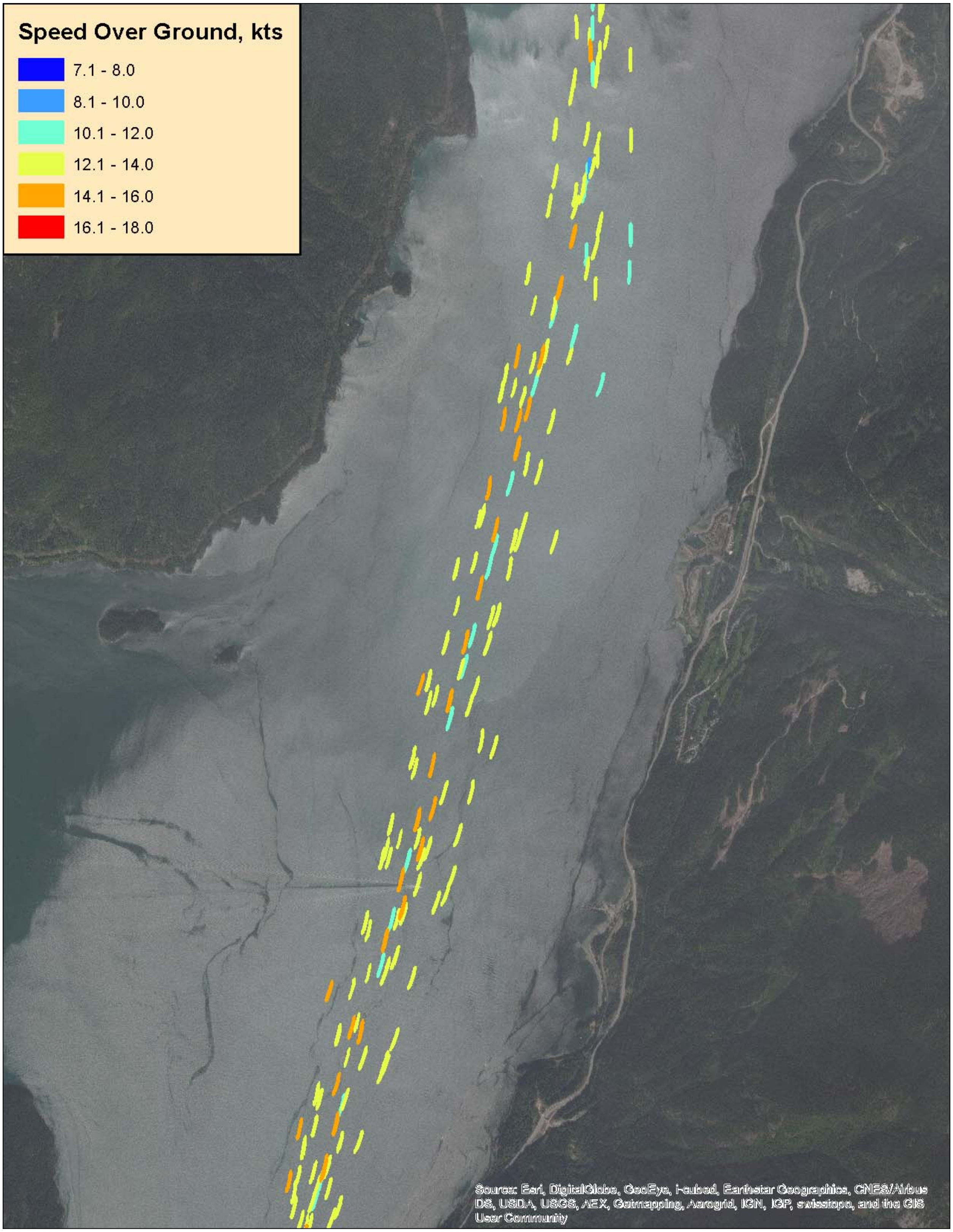
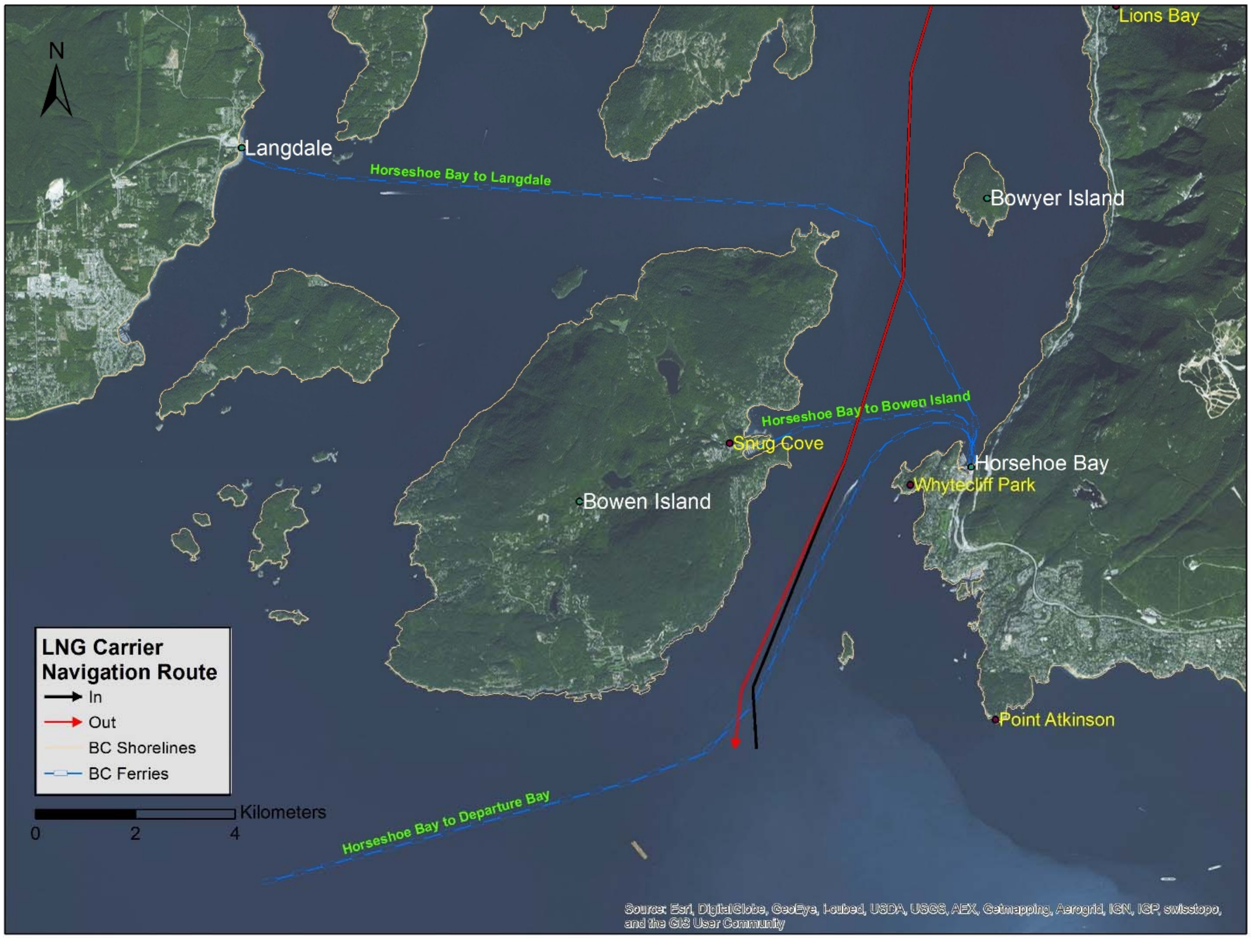


Figure 2-9: Example distribution of vessel transit speeds and positions near Oliver's Landing and Porteau Cove.

2.3.4 BC Ferry Routes

The existing BC Ferries vehicle ferry routes within Howe Sound are summarized in Figure 2-10. The mainland ferry berth is located at Horseshoe Bay from which vehicle ferry routes connect to Nanaimo, the Sunshine Coast at Langdale (Figure 2-11), and Bowen Island (Figure 2-12). Per the traffic data provided in Appendix B, ferry transits to Langdale and Bowen Island number 10-20 transits per day.

A scheduled water taxi service (Figure 2-13) provides passenger-only access between Langdale, Gambier Island, and Keats Island. The water taxis are not considered further in this study as their wakes from these passenger ferries can be expected to be of the same order of magnitude as recreational vessels in use within Howe Sound.



Source: Esri, DigitalGlobe, GeoEye, i-cubed, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community

Figure 2-10: Existing BC ferry routes within Howe Sound.

Figure 2-11: Queen of Coquitlam (left), Queen of Surrey (right). Source: *BC Ferries (2015)*.

Figure 2-12: Bowen Queen (left), Queen of Capilano (right). Source: *BC Ferries (2015)*.

Figure 2-13: Stormaway IV (left), Mercury (right). Source: *WWW (2015)*.

Particulars of the ferries considered in the study are summarized in Table 2-5.

Table 2-5: Particulars of BC ferries operating on routes within Howe Sound.

Route	**Sunshine Coast (Langdale) to Horseshoe Bay (West Vancouver)**		**Snug Cove (Bowen Island) to Horseshoe Bay (West Vancouver)**	
Vessel Particulars	**Queen of Coquitlam**	**Queen of Surrey**	**Bowen Queen**	**Queen of Capilano**
Vessel type	BC Ferry	BC Ferry	BC Ferry	BC Ferry
Length overall	139.3 m	139.3 m	85.0 m	96.0 m
Waterline length	130.1 m	127.2 m	80.8 m	91.2 m
Beam	27.1 m	27.0 m	18.7 m	21.2 m
Draft	5.3 m	6.0 m	4.0 m	4.4 m
Capacity	1,488 passengers and crew 360 vehicles	1,488 passengers and crew 360 vehicles	400 passengers and crew 70 vehicles	451 passengers and crew 85 vehicles
Gross tonnage	13,646	6,969	1,476	2,885
Displacement	6,465 tonnes	6,556 tonnes	1,637 tonnes	2,500 tonnes
Deadweight tonnage	1,496 tonnes	1,099 tonnes	515 tonnes	602 tonnes
Propulsion	8,602 kW	8,716 kW	2,683 kW	5,445 kW
Service speed	19 knots	19 knots	14 knots	14 knots
Maximum Speed	20.5 knots	20.5 knots	14.5 knots	14.6 knots

2.3.5 Historical BC Ferries

Because the PacifiCat car ferries in service from 1999 to 2000 reportedly produced significant wake wash on shores, they are included in this study for comparison. Two vessels in the series were initially employed for service between Horseshoe Bay (West Vancouver) and Departure Bay (Nanaimo) *(Wikipedia, 2015)*.

When operated at full speed, the PacifiCat vessels created a wake which was reported to have damaged waterfront wharves and property in coastal areas near the two terminals. Avoiding these effects required that the ferries reduce speed in certain areas and alter course in others, reducing their speed advantage. Complaints of the wash of the ships' wake ultimately forced the ferries to take a longer route, and operate a slower speed around Bowen Island.

Table 2-6 summarizes the principal particulars of the PacifiCat vessels.

Table 2-6: Particulars of PacifiCat Fast Ferries.

Vessel Particulars	PacifiCat Explorer PacifiCat Discovery
Length overall	122.5 m
Waterline length	96.0 m
Beam	25.8 m
Beam of hulls	6.0 m
Draft	3.76 m
Hull type	Dual-hulled catamaran
Capacity	1,000 passengers and crew 250 vehicles
Gross tonnage	9,022 tonnes
Displacement	1,885 tonnes
Deadweight tonnage	518 tonnes
Propulsion	4×6,500 kW diesel engines
Service speed, fully laden	34 knots
Top speed, empty	45 knots

3. THEORETICAL BACKGROUND

A vessel in transit will produce a particular wake pattern, which is outlined in Figure 3-1, adopted from *Schierech (2001)*. As the vessel displaces water during its passage a varying pressure distribution develops along the hull of the vessel producing an increased pressure at the bow and stern and a pressure drop along the midsection. The associated pressure gradients produce waves that propagate out from the bow and the stern of the vessel.

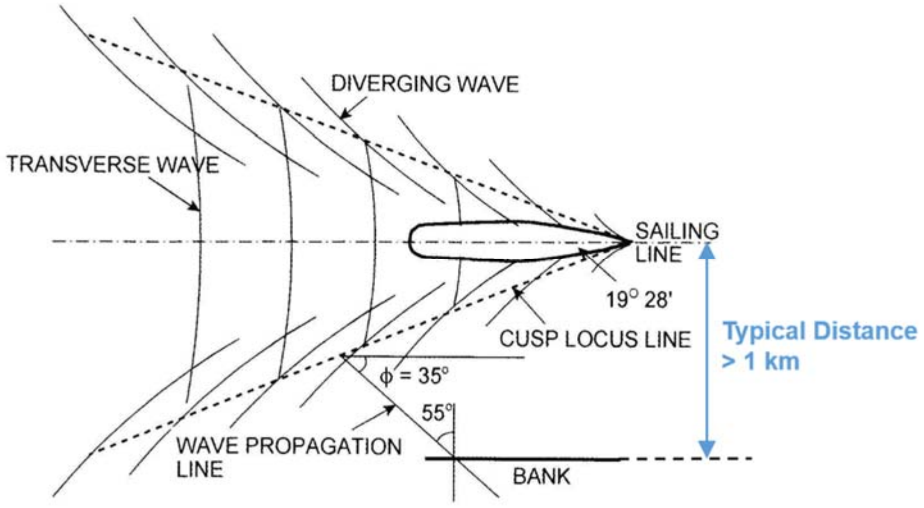


Figure 3-1: Vessel wake pattern (adopted from *Schierech, 2001*).

The waves emanating from the bow (Figure 3-1) are commonly named bow wake and follow a diverging pattern along the path of the vessel as they propagate out from the sailing line. A series of transverse waves, stern waves, propagate along the sailing line in the direction opposite to the vessel transit.

The stern waves are typically smaller than the bow wake. The largest wave heights are encountered where the transverse waves and the diverging waves intersect, which occurs along the cusp locus line, which has been found to form an angle of 19.28° relative to the sailing line.

A detailed derivation of vessel wake is highly complex as it depends on the particular hull shape of the vessel and essentially its frictional resistance during transit. It is only with modern computational methods that solutions of the underlying equations of physics are starting to develop, although the mathematics involved is extensive and computationally very intensive. The bulk of the present research has focused on developing semi-empirical relationships to describe the overall characteristics of vessel wakes. The main parameters governing vessel wake formation have been identified to be:

- The speed of the vessel, with increasing speed yielding an increase in wave heights.
- The water depth, with decreasing water depth producing an increase in wave heights.
- The Froude Number, which relates the above parameters to the celerity (travel speed) of a shallow-water wave, and in the case of deep water, to the overall dimension of the vessel.

As waves propagate out from the sailing line, the wave height attenuates with distance traveled and the wake become less prominent. Table 5-1 indicates that all the locations of interest along the LNGC's navigation route within Howe Sound are at least 1 kilometer away from the LNGC's sailing line.

Other parameters that affect wake formation, but less well understood in past research include the hull shape of the vessel, its draft, underkeel clearance, and confinement of the water body surrounding the vessel.

In the following sections, two methods adopted in the present study are described. For consistency, the symbols used in each method are unified to represent the same input parameter.

3.1 KRIEBEL AND SEELIG METHOD

Kriebel and Seelig (2005) propose an empirical model, approximating the variation of secondary wave heights H with distance y as:

$$H = \frac{\beta V_s^2}{g}(F^* - 0.1)^2 \left(\frac{y}{L}\right)^{-\frac{1}{3}}$$

Where V_s is the vessel speed, g the acceleration due to gravity, y is the distance from the sailing line, L is the length of the vessel, F^* is a modified Froude number, and β an empirical coefficient based on the hull shape of the vessel.

Kriebel and Seelig state that the Froude number F is defined by the water depth-to-draft ratio h/D. They further state that vessels transiting deep water ($h/D > 5$) produce a wake size that depends on the length-based Froude number F_L, and vessels transiting shallow water ($h/D < 1.5$) produce a wake size that depends on the depth-based Froude number F_d. Between these two water depths, Kriebel and Seelig determined that a modified Froude number F^* was more appropriate.

$$F^* = F_L exp(\alpha\, D/h)$$

$$\alpha = 2.35(1 - C_b)$$

Where D is the vessel draft, h the water depth, and α an empirical coefficient dependent on the vessel block coefficient cb, defined as:

$$C_b = \frac{\nabla}{LBD}$$

Where ∇ is the volume displacement and L, B, and D is the length, beam, and draft of the vessel.

The coefficient b is defined as:

$$\beta = 1 + 8 \cdot tanh\left(0.45\left(\frac{L}{L_e}\right) - 2\right)^3$$

Where L_e is the entrance length.

3.2 PIANC METHOD

The approach by *Verhey et al. (1989)* has been adopted in the guidance provided in *PIANC (1987)*.

The variation of wave height with distance can be described by:

$$\frac{H_i}{h} = \alpha_1 \left(\frac{s}{h}\right)^{-1/3} F_s^{\alpha_3}$$

Where H_i is the wave height, h is the water depth, s is the distance from the sailing line and F_s is the Froude number given by:

$$F_s = \frac{V_s}{\sqrt{gh}}$$

Where V_s is the vessel speed and g is the acceleration due to gravity.

The parameter α_1 has been found to vary by vessel type and loading state. A value of $\alpha_1 = 1$ is recommended as a value for predicting the mean estimate of wave heights across a wide range of vessels. A value of $\alpha_1 = 1.2$ is recommended as an upper bound of wave height estimates. A value of $\alpha_3 = 4.0$ has been confirmed in several field studies.

Research by Verhey and Bogaerts relates α_1, the parameter which scales the magnitude of the wake relative to the vessel hull shape as: $\alpha_1 = \alpha_2\, T/L_e$, where T is the vessel draft and L_e the entrance length. The entrance length is the distance from the vessel's bow to the commencement of the parallel mid-body section and is a measure of the curvature of the bow.

LNG carriers have relatively fine lines and in the present case α_1 would then be estimated to range from α_1 = 0.24 to 0.64. This is based on estimates of α_2 by *Verhey et al. (1989)* ranging from 1.5 to 4.0.

Additional characteristics proportions of the wake characteristics can be determined as follows per *CEM (2006)*. The speed of wake propagation (celerity) is given by:

$$C = V_s\, cos(\theta)$$

Where C is the celerity, V_s is the vessel speed, and θ is the angle of wave propagation with respect to the sailing line as defined in Figure 3-1. The angle of wave propagation has been found to be related to the Froude Number as follows:

$$\theta = 35.27°\left(1 - e^{12(F_S-1)}\right)$$

Where F_s is the Froude Number and e is the exponential function.

The wave length is determined from the dispersion relation given by:

$$C^2 = \frac{gL}{2\pi}\tanh\left(\frac{2\pi h}{L}\right)$$

Where C is the celerity, h is the water depth, L is the wave length, and g the acceleration due to gravity. The wave period, T, can be resolved from:

$$T = \frac{L}{C}$$

In deep water where the propagation of waves is unaffected by the bottom topography, as is the case for vessel wake propagation within Howe Sound, the wave length and wave period terms reduce to:

$$L = \frac{2\pi}{g}C^2$$

And

$$T = \frac{2\pi}{g}C$$

3.3 PRELIMINARY WAKE ASSESSMENT

Based on the stated equations, it’s possible to develop a simple preliminary assessment of the wake characteristics associated with the vessels under consideration as summarized in Table 3-1. The primary findings are in terms of wave direction of propagation, wave period, and wave length. Findings regarding wake wave heights are provided in Chapter 5.

Table 3-1: Comparison of essential wake parameters.

Vessel Parameters	Vessels for Woodfibre				Existing BC Ferries		Historical
	LNGC	Tugs	Garibaldi II	Quinsam	Sunshine Coast	Bowen Island	PacifiCat
Service Speed	10 knots	10 knots	10 knots	12 knots	19 knots	14 knots	34 knots
Froude Number	0.10	0.32	0.30	0.22	0.27	0.25	0.57
Wave Direction	35.3°	35.3°	35.3°	35.3°	35.3°	35.3°	35.1°
Celerity	4.2 m/s	4.2 m/s	4.2 m/s	5.0 m/s	8.0 m/s	5.9 m/s	14.3 m/s
Wave Period	2.7 s	2.7 s	2.7 s	3.2 s	5.1 s	3.8 s	9.2 s
Wave Length	11.3 m	11.3 m	11.3 m	16.3 m	40.8 m	22.2 m	131.3 m

The results summarized in Table 3-1 support the following conclusions:

- The Froude number for the LNGC is F=0.1, which means that it will be at the verge of wake formation. Several field studies have found F≈0.1 as the threshold for wake wave formation in deep water.
- The tugs operate at higher Froude numbers and therefore more readily produce a wake.
- The wave period and wave lengths for vessels associated with the Woodfibre LNG Project are in the range of typical wind-generated waves.
- Wakes generated by the BC Ferries have somewhat longer wave periods.
- Wave lengths of wake produced by project-related vessels will be at least half of BC Ferry wakes.
- The former PacifiCat fast ferries produced wakes with wave periods of around 9 seconds, which is comparable to ocean swell waves.

4. ANALYSIS OF WAKE PATTERNS

Wake patterns produced by vessels in transit can be approximated by the free-surface elevation Z given as:

$$Z(x,y) = \frac{1}{\pi^2}\Re\int_{-\pi/2}^{\pi/2}\int_{0}^{\infty} e^{-ik(xcos\theta+ysin\theta)}\,\frac{k^2(P+iQ)}{k-k_0sec^2\theta}\,dk\,d\theta$$

Where

$$P+iQ = -\frac{1}{ikcos\theta}\iint_R Y_\xi(\xi,\zeta)e^{ikcos\theta\xi+k\zeta}\,d\xi d\zeta$$

Which is termed a Fourier-Kochin representation. The method is described in *Tuck et al. (2001)* and *Tuck (2003)* and has been demonstrated to produce results comparable to commercial Computational Fluid Dynamic (CFD) codes, *Revathi et al. (2012)*.

Mathematically the method relies on thin-ship theory; that the vessel moves at a steady constant speed; and the water depth is infinite. It is suitable for application to Howe Sound in that vessel hulls are relatively elongate, vessels move at a fairly constant service speed when in transit; and the water is deep.

The particular application of the method primarily resolves the far field wake pattern propagating aft and away from the vessel, but does not resolve the water surface elevation right at the hull. Additionally, because the method assumes a simplified hull-shape, wave height estimates computed are only indicative, and would need to be calibrated with field data, or comparative CFD analysis that has been verified with field measurements.

4.1 LNG CARRIERS

Figure 4-1 shows a plan view of the wake pattern computed for the LNG carrier using the method in *Tuck et al. (2001)*. The cyan background is representative of the mean sea level. Wave crests of increasing height are indicated in yellow, orange, and red colors. The crests of the very highest of the waves are indicated in white. These are typically seen in the top portion of the figure which is at the stern of the vessel. The vessel sailing path is up in the figure, viz. a heading north through Howe Sound.

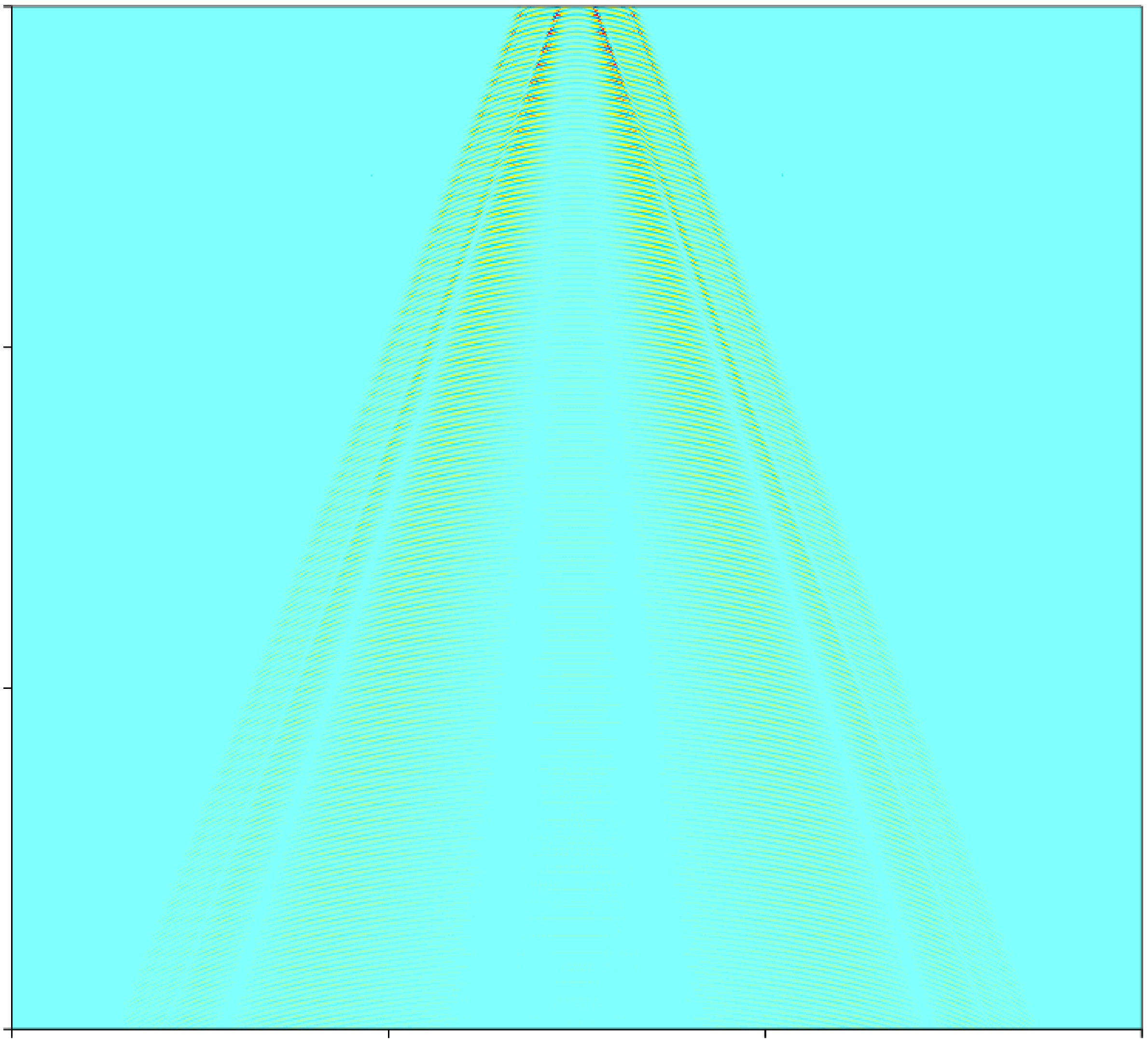


Figure 4-1: Plan view of vessel wake computed for LNG Carrier over a 3 km × 3 km area.

It should be noted that only wave components associated with the vessel wake are shown in the figure. Waves representative of the natural sea state are therefore not shown.

The 3 km × 3 km area of coverage was selected because this extent in most cases will cover the over-water distance to shore relative to the sailing line, viz. an extent 1½ km on each side of the vessel.

Details of the figure are barely discernible at the scale shown, but it can be seen that the highest wake waves occur immediate aft of the vessel (top of figure) and decrease with distance away from the vessel (towards bottom of figure). By isolating only those wave components attributed to the wake formation, the figure does show that remnants of the wake theoretically can travel quite far away from the vessel.

Figure 4-2 provides example transects of the wake behind the vessel. The lightest blue color is representative of a transect relative close to the vessel. Progressively darker blue colors reflect transects at increasing distance from the vessel, the transects shown were taken at distances from the vessel of approximately 10 m, 500 m, 1000 m, 1600 m, 3000 m, and 4300 m. The latter two transects (darkest blue color) are representative of the wake waves that would arrive at the shore 1-1.5 km from the sailing line, which is the typical distance to shore where the sound is at its narrowest. The dotted red line is included to highlight the decrease (attenuation) in wave height with distance traveled away from the sailing line.

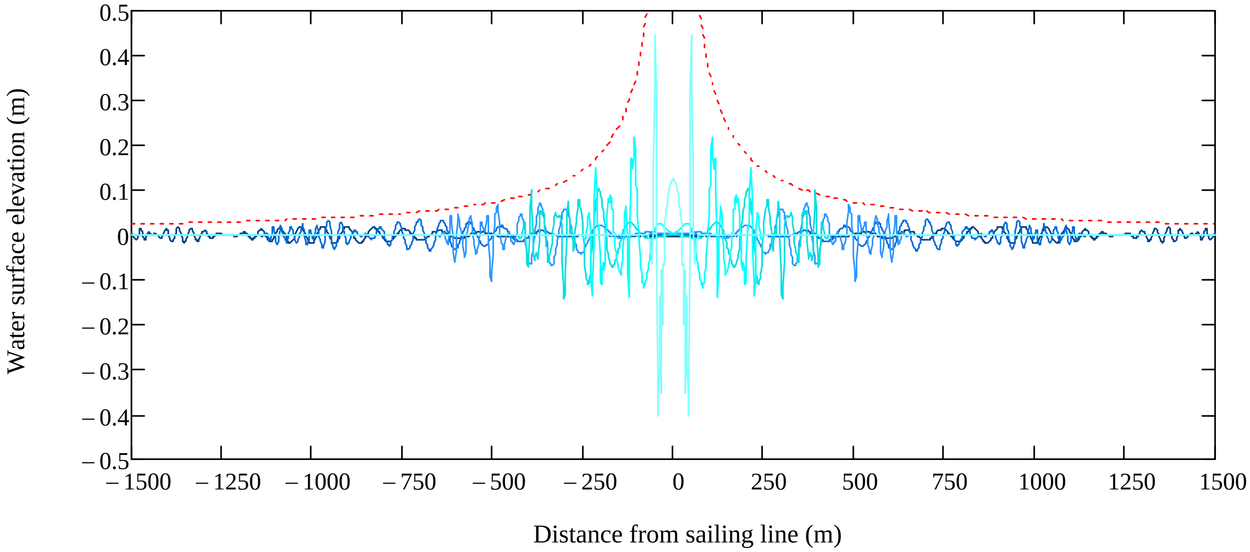


Figure 4-2: LNGC wake transects.

4.1.1 Comparative Results

For reference, DHI (2012), analyzed vessel-generated wake waves for tankers and tugs in the Kitkiata Inlet and Principe Channel. The study utilized RANS based CFD modeling to determine wake waves for a loaded VLCC at 16 knots, which compares to the LNGC anticipated for Woodfibre as summarized in Table 4-1. In very general terms, these vessels are comparable by being large ocean-going vessels with similar order-of-magnitude dimensions. However, the following aspects would imply that the VLCC would produce a larger wake than the LNGC:

- VLCC is longer and wider than LNGC
- VLCC has draft nearly twice as deep as LNGC

- VLCC has larger displacement; and
- VLCC was traveling at higher speed.

Table 4-1: Comparison of VLCC Tanker particulars from *DHI (2012)* CFD study with Woodfibre LNGC.

Vessel Particular	*VLCC Tanker (DHI, 2012)*	LNGC *(Current Study)*
Length overall (LOA)	343.7 m	298.0 m
Length between perpendiculars (LBP)	327.0 m	279.0 m
Breadth	56.4 m	45.8 m
Draft	21.8 m	12.9 m
Displacement	250,612 tonnes	131,668 tonnes
Speed	16 knots	10 knots

From the CFD modeling for the VLCC *(DHI 2012)*, it was found that the maximum wave height 1½ LBP (vessel length) from the vessel track was less than 0.1 m for a water depth of 250 m.

For a water depth of 90 m, with wave height 1½ LBP from the ship track, the maximum wave height was modeled at 0.18 m.

The associated wave period was estimated at 4.3 s from the CFD results, and the direction of the wave propagation relative to the sailing direction was estimated at 35°.

The findings of the CFD analysis thus supports the fact that wakes from large ocean-going vessels in deep water can be expected to be relatively small.

4.2 TUGS

Figure 4-1 shows a plan view of the wake pattern computed for a Seaspan Raven Class tug. As for the LNGC (Figure 4-1), the individual wave crests in the wake pattern are barely visible at the scale shown. It can be seen that the highest wake waves occur immediate aft of the vessel (top of figure) and decrease with distance away from the vessel (towards bottom of figure).

What is not immediately apparent by comparison of Figure 4-1 and Figure 4-3, but demonstrated elsewhere in this report is that tugs despite being diminutive in size compared to LNG carriers, typically produce a more pronounced wake. This is primarily because tugs present a more blunt hull shape and travel at a higher relative speed (i.e. have a higher Froude number).

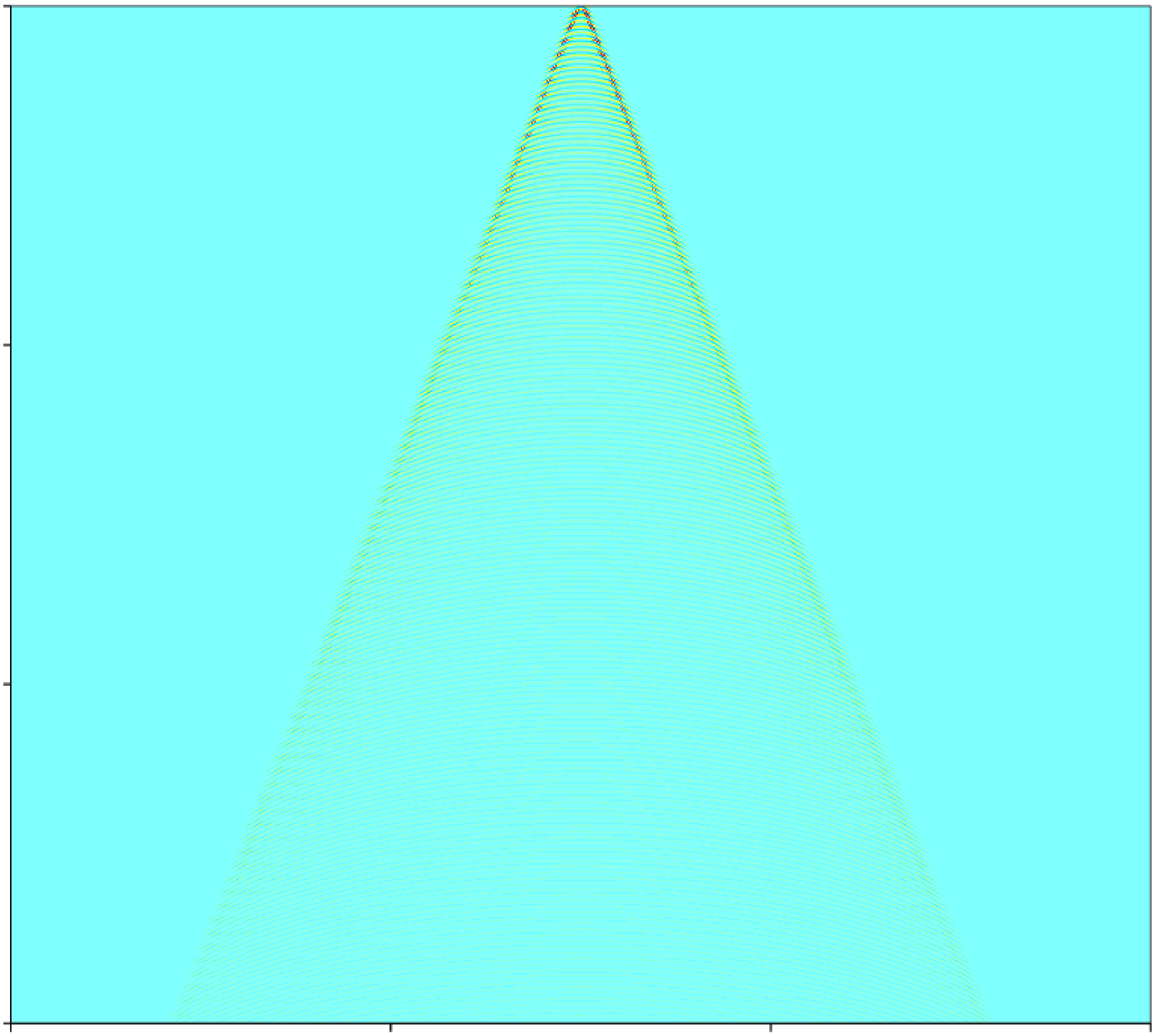


Figure 4-3: Plan view of vessel wake computed for Seaspan Tug over a 3 km × 3 km area.

Figure 4-4 shows transects of the wake behind the vessel at distances of 500 m, 1000 m, 1500 m, 2500 m, 3500 m, and 4300 m. The latter two transects (darkest blue color) are representative of the wake waves that would arrive at the shore 1-1.5 km from the sailing line. The dotted red line is included to highlight the decrease (attenuation) in wave height with distance traveled away from the sailing line.

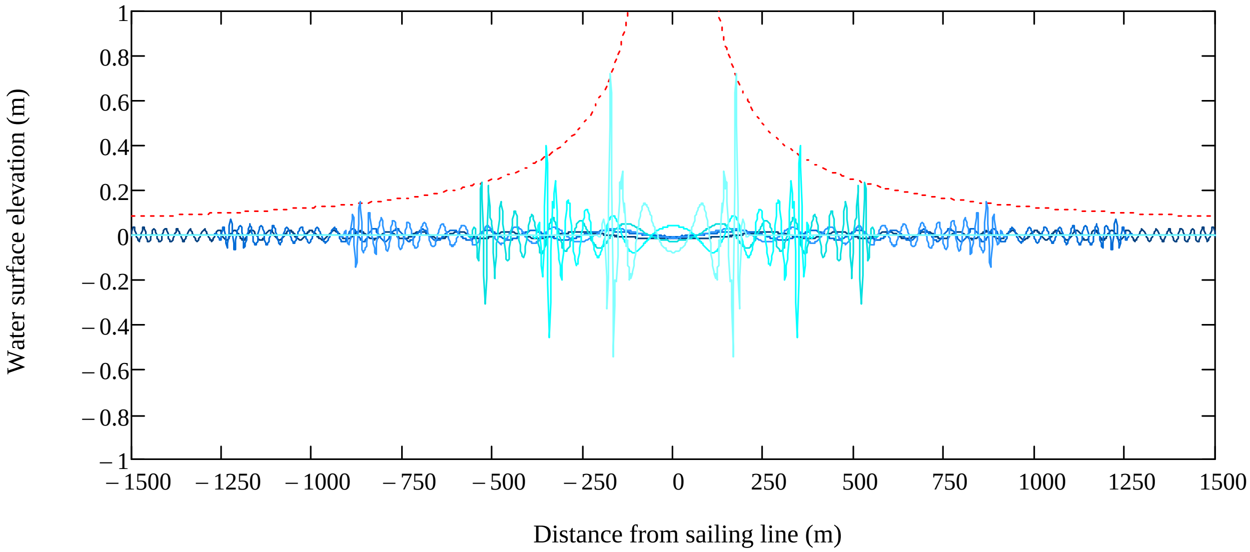


Figure 4-4: Seaspan Tug wake transects.

4.2.1 Comparative Results

Figure 4-5 provided by Robert Allan Naval Architects and Marine Engineers illustrates the variation in wake height with distance for a 40 m tug at speeds ranging from 12 to 15 knots. These results were developed with CFD analysis.

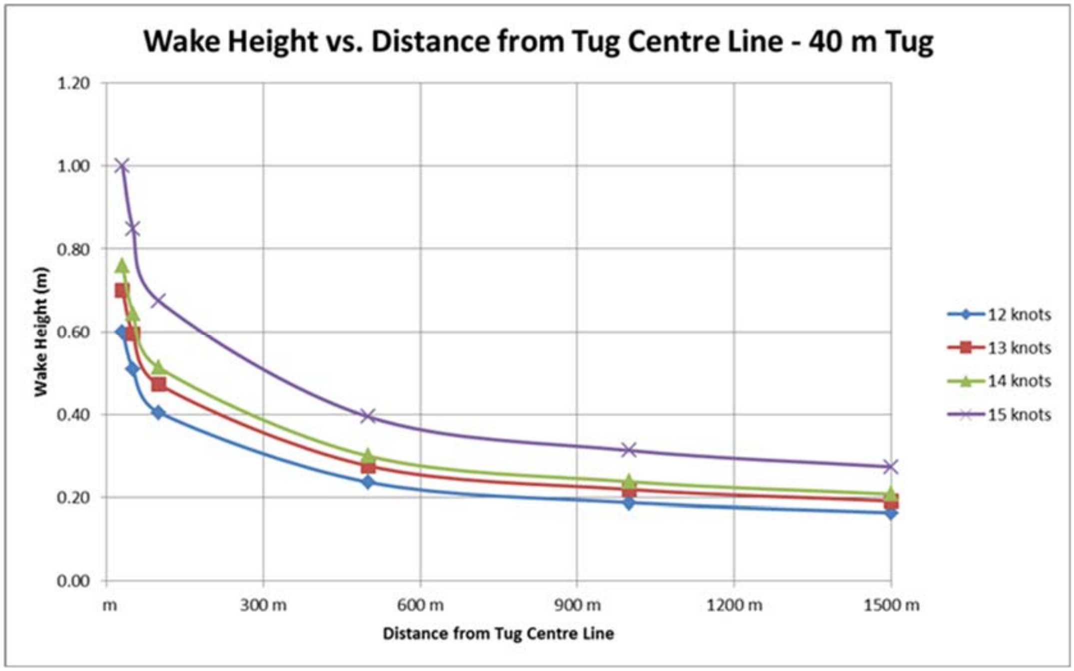


Figure 4-5: Example wake height variation with distance for a 40 m tug. Source: Robert Allan Ltd.

The data shown in Figure 4-5 is for a tug which is larger than the ones intended for project-related use and traveling at higher speeds of 12-15 knots versus the 8-10 knots anticipated for transits to the Woodfibre site. In terms of Froude number, the curves shown in Figure 4-5 for speeds of 12-13 knots (blue and red line) are the ones that compare to the dotted red line in Figure 4-4.

Further, *DHI (2012)* utilized CFD analysis to determine the magnitude of wakes from tugs associated with escort of tankers in the Kitkiata Inlet and Principe Channel. The study determined wake waves for tugs comparable, but slightly larger than those anticipated for the project as summarized in Table 4-2. However, the following aspects would imply that the tugs investigated in the *DHI (2012)* study would produce larger wakes than the tugs planned for Woodfibre:

- Tugs in DHI study were longer and wider than those intended for Woodfibre
- Draft of tugs in DHI Study was deeper than that of tugs planned for Woodfibre; and
- Tugs in DHI study were traveling at a slightly higher speed.

Table 4-2: Comparison of VLCC Tanker particulars from *DHI (2012)* CFD study with Woodfibre LNGC.

Vessel Particular	*Tug (DHI, 2012)*	Seaspan Tugs *(Current Study)*
Length between perpendiculars (LBP)	45.0 m	25.9 m
Breadth	16.3 m	12.6 m
Draft	7.1 m	5.4 m
Speed	12 knots	10 knots

For the tug travelling at 12 knots, it was found that the maximum wave height 1 LBP from the route was 0.15-0.20 m. The associated wave period was estimated from the CFD modeling at 3.3 s, and the direction of the wave propagation relative to the sailing direction was estimated at 35°.

4.3 LNG CARRIER WITH TUG ESCORT

Transit of the LNGC with tug escort may take several forms, but the tug escort pattern anticipated for transits to the Woodfibre site is expected to utilize two tethered escort tugs aft of the LNGC and one untethered tug approximately 500 m ahead leading the transit.

Figure 4-6 shows a schematic of the planned vessel formation. The two tugs aft are tethered to the LNGC in order to provide emergency assistance during the transit if needed. Under normal operating conditions the LNGCs do not need any assistance with manoeuvring under their own power; however, in the unlikely event of a steering or propulsion failure, the escort tugs are available to immediately render any assistance needed in stopping or turning the vessel.

The tug ahead functions as a look ahead during transit and assists with manoeuvring of the LNGC as needed for berthing and unberthing at the FSO. This vessel also serves as a backup tug to the two tugs astern.

Figure 4-7 shows a plan view of the wake pattern computed for an LNGC with three escort tugs. The layout of vessels is per Figure 4-6. Because the wakes from the tugs are more pronounced than that of the LNGC, the wake produced by the LNGC is barely noticeable in the figure.

Because the vessels all transit at the same (sub-critical) speed, the geometry of the wakes produces is the same for all of the vessels, i.e. the wake forms the characteristic V-shape.

For an observer at a fixed location, the wake arriving will consist of first the wake from the leading tug, next the wake from the LNGC, and lastly the wake from the two stern tugs.

Because of the separation between vessels in terms of distance, the wakes appear as separate wave trains. For the stern tugs, which may transit in close proximity to each other, the wave trains from their individual wakes may coalesce into a mixed trains of waves depending on their location relative to each other.

In Figure 4-7, a slight offset of the stern tugs has been assumed to illustrate the effect, which can be seen approximately center of the figure to the right where the wake patterns from the tugs merge into one.

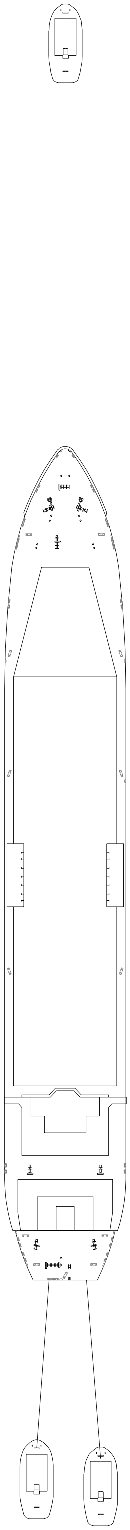


Figure 4-6: LNGC and Escort tugs

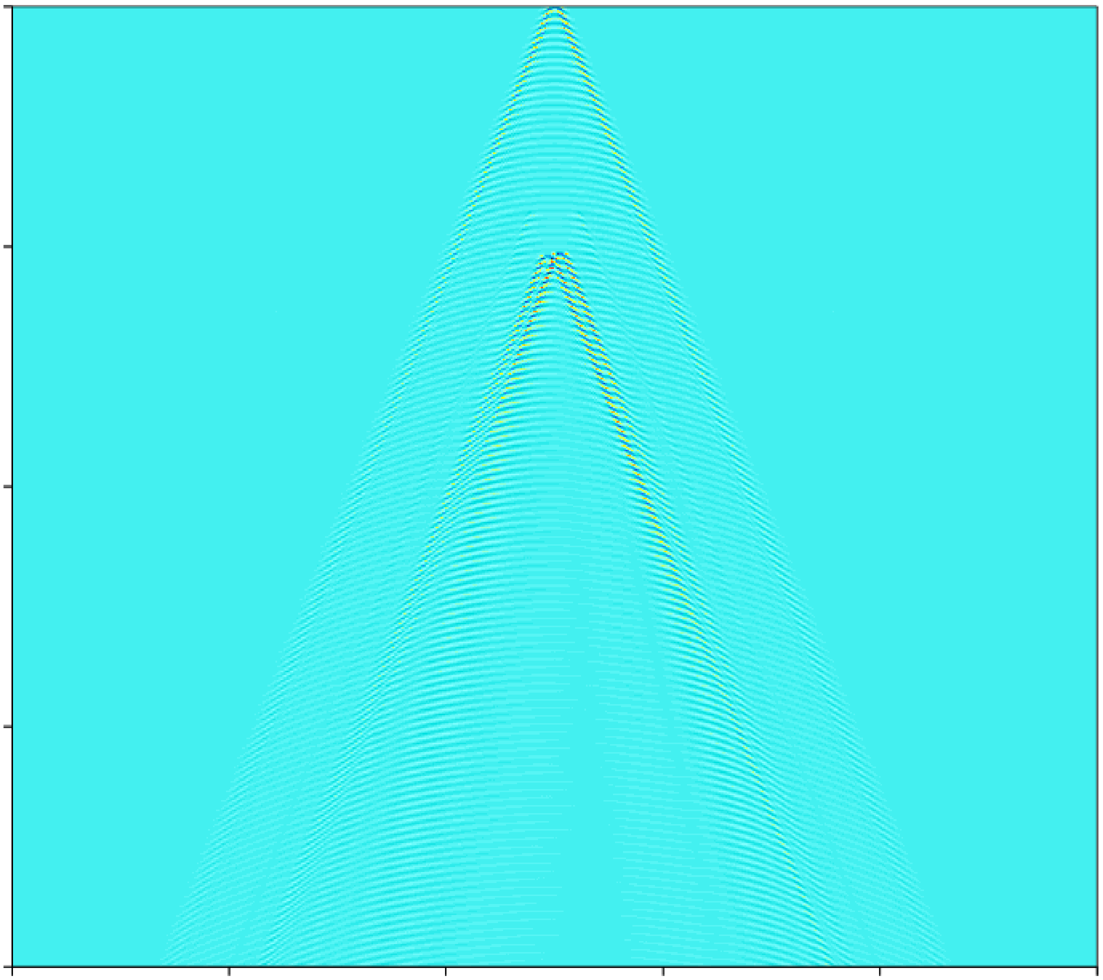


Figure 4-7: Plan view of vessel wake computed for LNGC with three escort tugs over a 2 km × 2 km area.

Figure 4-8 shows transects of the water surface elevation profiles as a function of distance from the sailing line. The purple line shows the wake contribution from the leading tug, the cyan line the wake from the LNGC, and the red and green lines the wakes from the port side and starboard side tugs astern. The combined water surface elevation is indicated with a heavier black line.

It should be noted that the underlying analysis is approximate in that the combined wave field has been determined by simple superposition of the individual wave trains. This, however, does not account for any wave interaction or shielding between vessels.

The analysis does illustrate that the resulting wave field is complex and each of the wake wave trains contributes to the variation of the combined wave field. It can also be seen that at times, the individual wave trains may work to partially cancel out each other, and may also combine into a momentarily higher wave. Although the interaction between the individual vessel wakes produces a complex wave field, the wave trains still attenuate with distance traveled away from the sailing line.

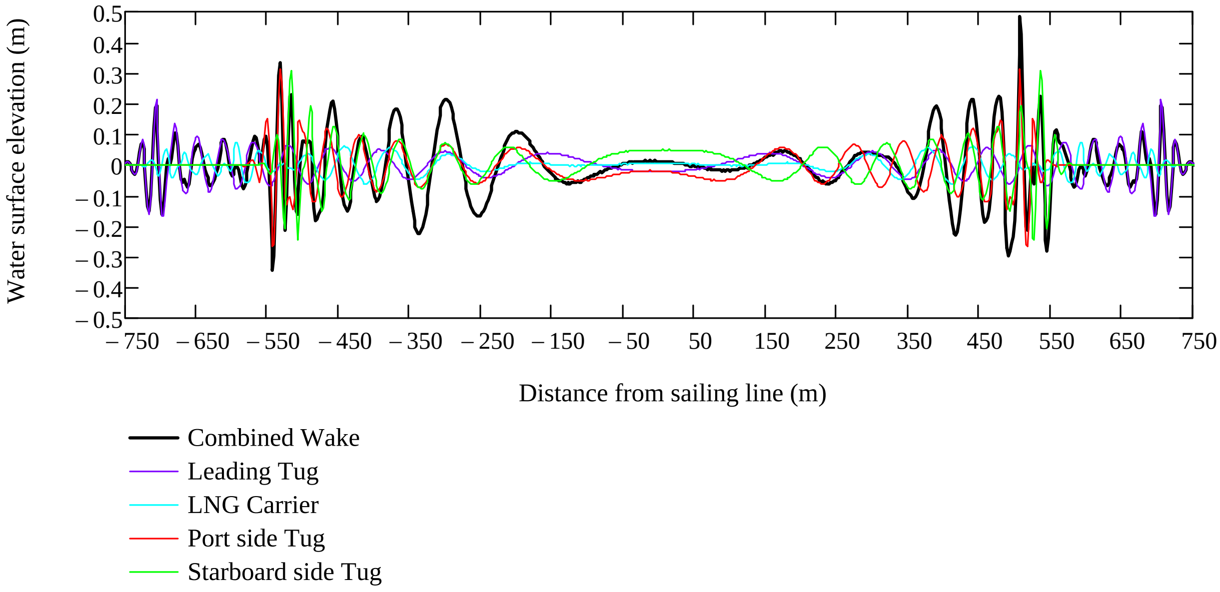


Figure 4-8: Combined wake from LNGC and three escort tugs.

For a sense of scale, Figure 4-9 compares the combined wakes from the LNGC and escort tugs to a sea state which has maximum wave heights of around 0.5 m. With the natural sea state included, it's apparent that the wake becomes less prominent, and not as easy to identify.

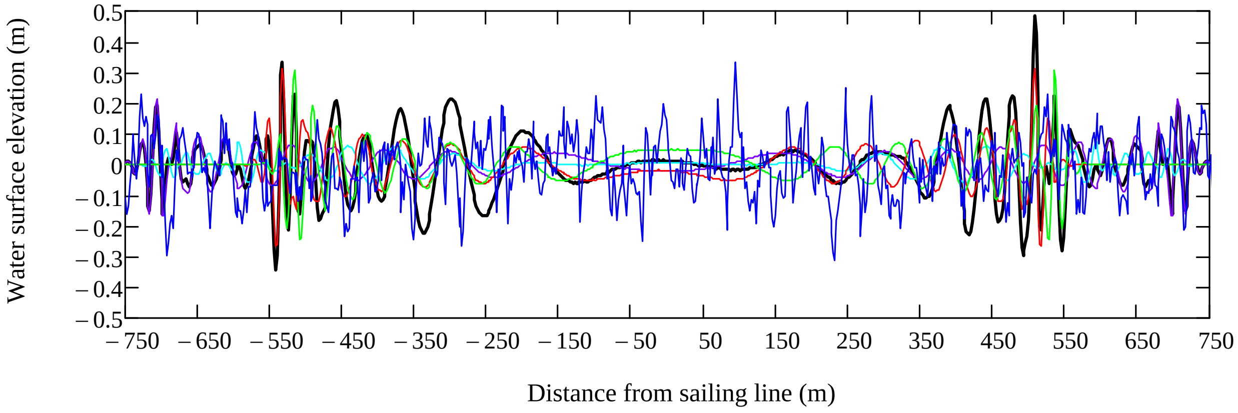


Figure 4-9: Wake from LNGC and three escort tugs combined with ambient sea state.

4.4 WOODFIBRE WORKER FERRY

The worker ferry for Woodfibre is intended to sail between Darrell Bay and Woodfibre. Figure 4-10 shows the wake pattern computed for the largest of the worker ferries considered, the MV Quinsam, at a speed of 12 knots (Table 2-4).

The Quinsam (Figure 2-7) is a car ferry operated by BC Ferries. In terms of size, the Quinsam is comparable to the ferries on the route to Bowen Island (Figure 2-12) and slightly smaller than ferries on the route to Langdale (Figure 2-11).

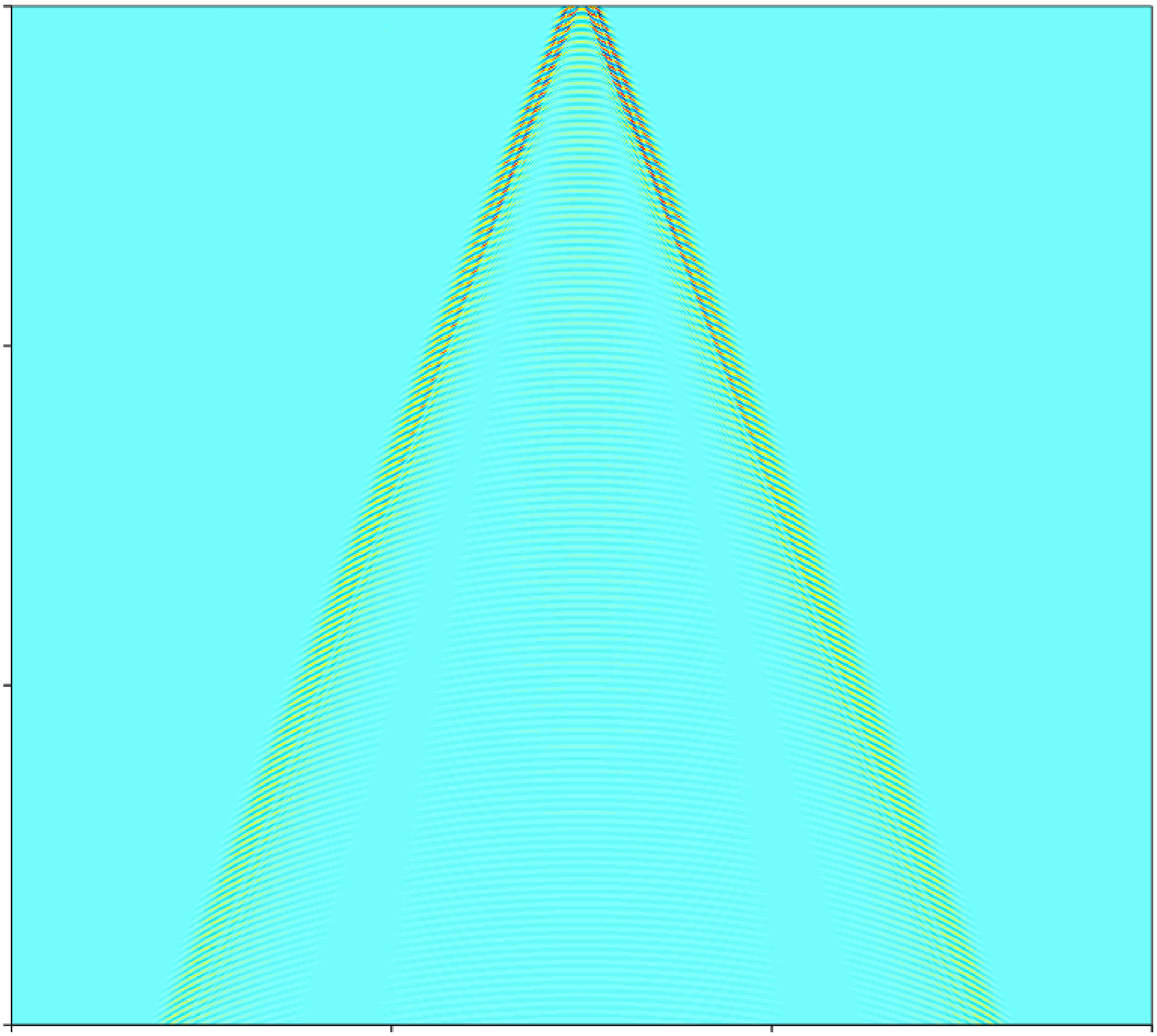


Figure 4-10: Plan view of vessel wake computed for largest Woodfibre worker ferry over a 3 km × 3 km area.

Transects of the wake behind the worker ferry are shown in Figure 4-11, at distances of 300 m, 1200 m, 1800 m, 2900 m, 3600 m, and 4300 m. The latter two transects (darkest blue color) are representative of the wake waves that would arrive at the shore 1-1.5 km from the sailing line. The dotted red line shows the decrease in wake wave height with distance from the sailing line.

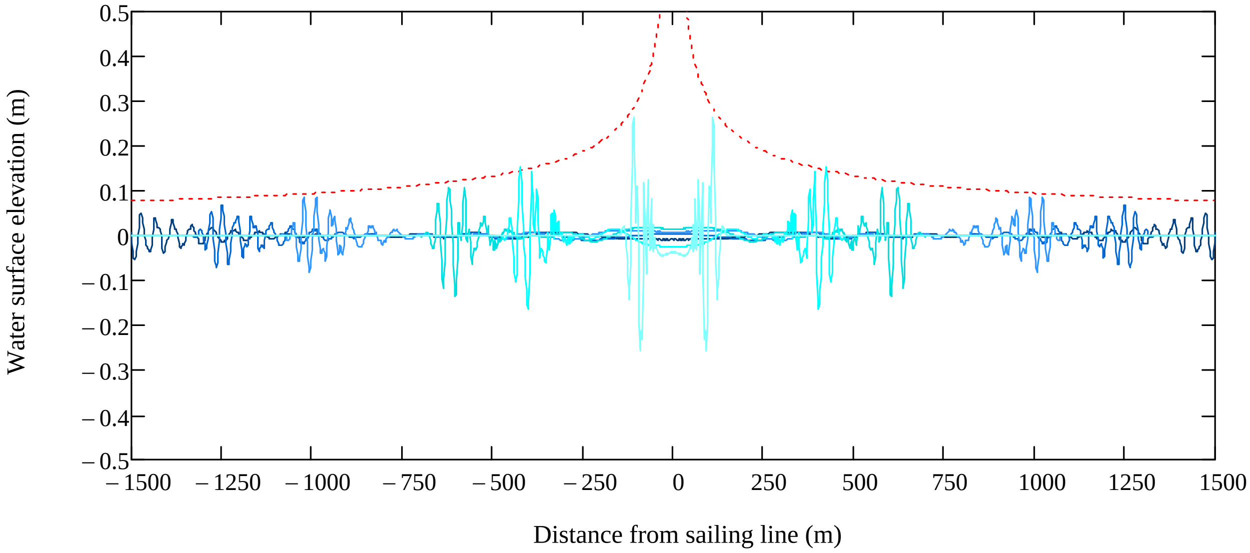


Figure 4-11: Woodfibre worker ferry wake transects.

4.5 BC FERRIES

The existing BC Ferries can be expected to produce a more substantial wake than that of the vessels traveling to the Woodfibre site. The primary reason being their service speed which is higher than that planned for the LNGC and tug transits, ref. Table 3-1.

Figure 4-12 captures vessel transit speeds in a wide region around the Strait of Georgia, Vancouver, Bellingham, Victoria, and the Strait of Juan de Fuca. The Woodfibre site is identified in blue text in the top part of the figure. The orange line between Horseshoe Bay and Langdale is indicative of the service speed of BC Ferries, which falls in the range of 17-19 knots.

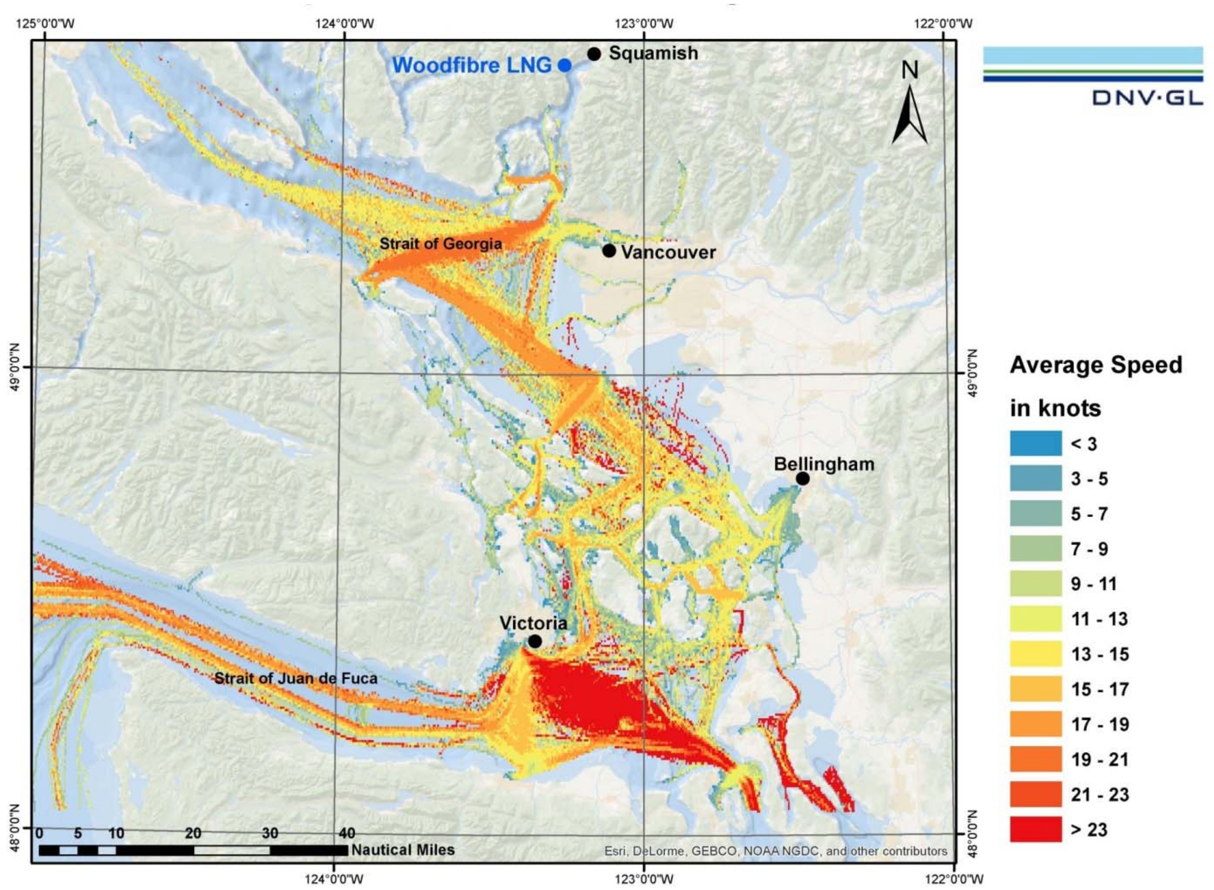


Figure 4-12: Speed profile for passenger vessels. ***Source: DNV via Valiance Maritime Consultants Limited.***

Figure 4-13 provides a plan view of the wake computed for one of the larger ferries on the route between Horseshoe Bay and Langdale. The ferries on the route to Bowen Island can be expected to produce slightly less of a wake as their service speed is somewhat lower.

Comparing with the results for the LNG Carriers and tugs (Figure 4-1 and Figure 4-3), the BC Ferry wakes have longer wave periods, and consequently longer waves (note the wider distance between yellow/cyan lines in Figure 4-13). The same findings are arrived at using the simplified analysis summarized in Table 3-1.

Figure 4-13 shows that wake produced by the BC Ferries theoretically can propagate to shores 1.0 km from their sailing line and further away. This is based on the analysis portrayed in Figure 4-13 where all other aspects of wave generation are omitted, such as wind-generated waves, and waves e.g. reflected back from rocky shorelines. These results indicate that wakes from the ferries may be noticeable at the shore in areas where the ferry routes come in closer under land. See for example the findings and commentary summarized in Appendix B. For reference, *ASL (1999)* acquired wake measurements for the BC Ferries MV Queen of Coquitlam and Queen of Alberni. The findings are summarized in *BCFC (2000)*, and were found to be comparable to the results developed in the present study.

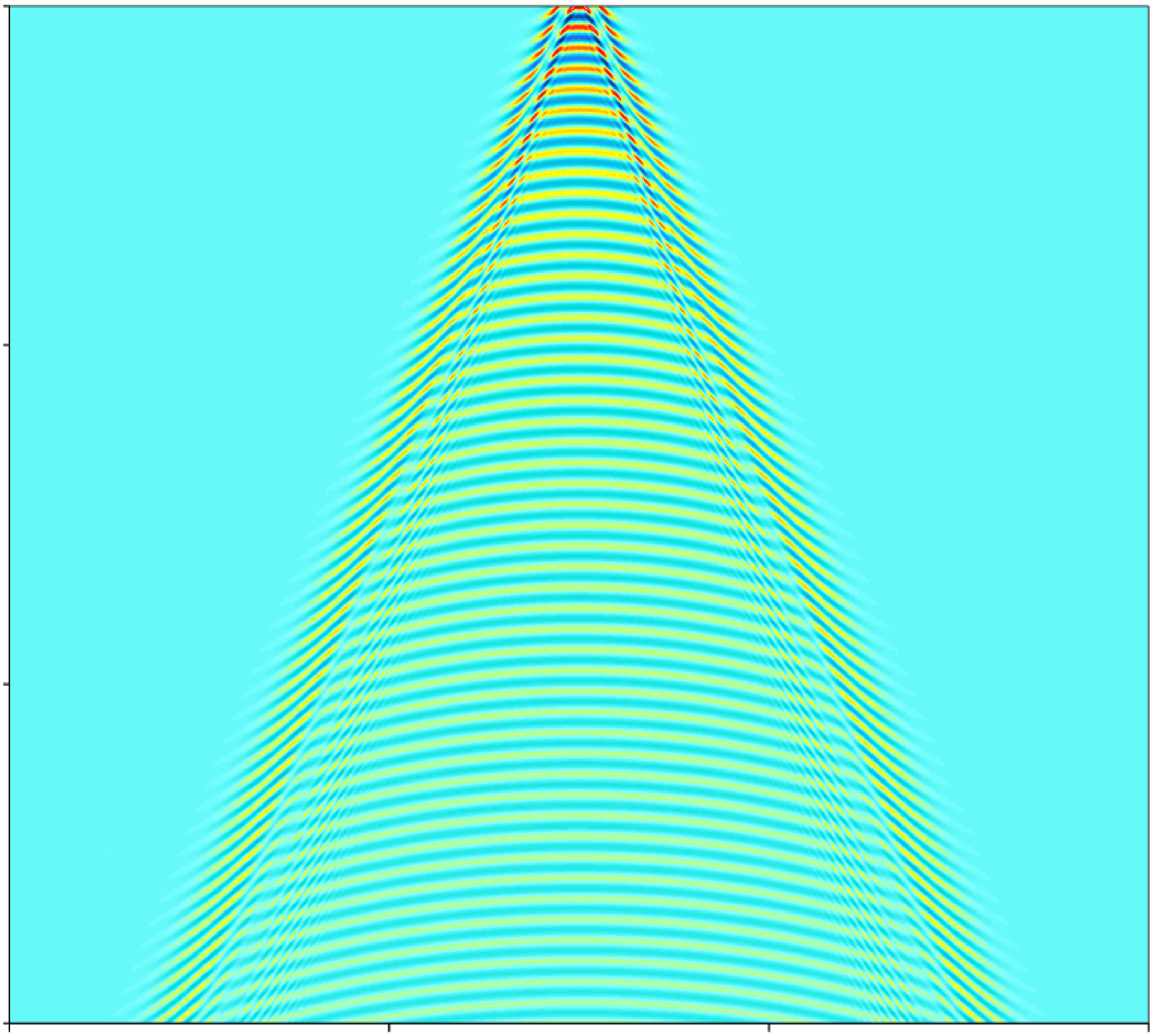


Figure 4-13: Plan view of vessel wake computed for BC Ferry over a 3 km × 3 km area.

Example transects of the water surface variation within the wake pattern are shown in Figure 4-14 taken at distances of 500 m, 1000 m, 1500 m, 2200 m, 3000 m, and 4300 m. Because the BC Ferries transit at higher speed and produce wake with longer waves, the wave height attenuation is not as rapid over distance as for the LNGC (Figure 4-2) and tugs (Figure 4-4).

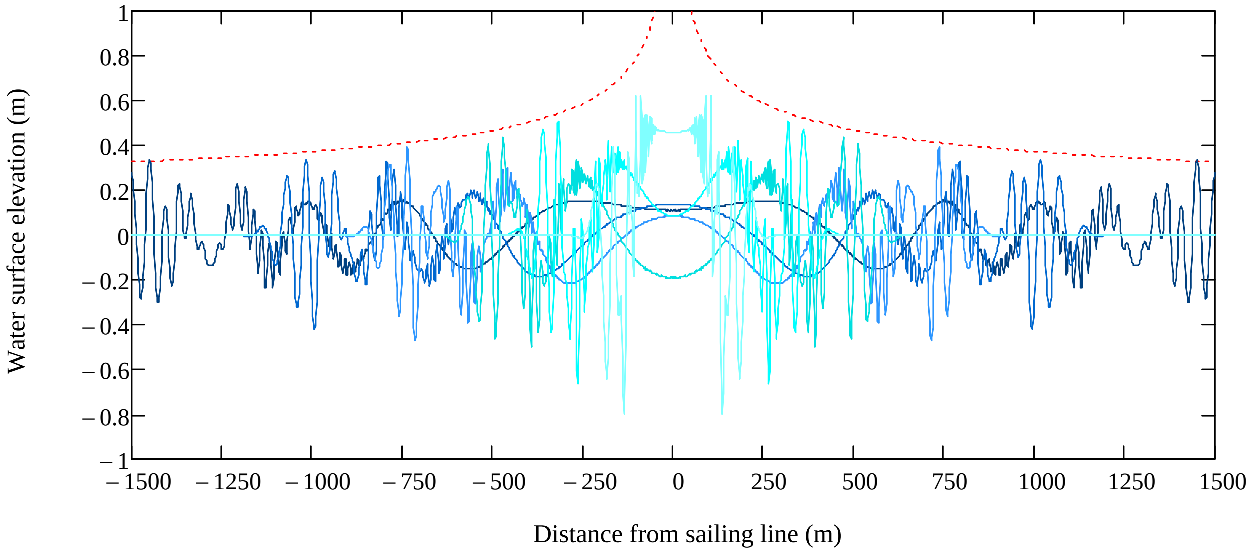


Figure 4-14: BC Ferry wake transects.

4.6 LNG CARRIER WITH TUG ESCORT AND BC FERRY

In order to compare the combined wave effects from an LNG carriers, escort tugs, and ferries, an analysis has been conducted for the case of an LNGC under tug escort with a BC ferry passing. The setting for the scenario is envisaged to be during inbound transit through the Queen Charlotte Channel, where the LNGC and tug escort could encounter ferries approaching or departing Horseshoe Bay. This area is relatively congested with up to 20 to 92 transits per day as seen on the chart of commercial marine traffic density included in Appendix A. During transit, the pilots onboard the LNGC will coordinate passage at Horseshoe Bay closely with ferry operators and other commercial vessels in the area.

Figure 4-15 shows an example of the wake computed for the LNGC and tug escort with ferries passing on each side of the LNGC. The ferry on the right hand side of the figure, starboard side to the LNGC and escort tugs, is assumed to be inbound while the ferry on the left hand side of the figure, port side to the LNGC and tugs is assumed to be outbound. The vessel outlines are not provided in the figure, but the wakes from the inbound and outbound ferries can be identified by having a more pronounced wake pattern (the V-patterns pointing up and down in the figure).

The ferries passing the LNGC and escort tugs will transit at a higher speed and the interference between the wake patterns from individual vessels will therefore vary. In the example shown, the timing has been selected such that the wake from the inbound ferry intersects that of the

LNGC and tugs, and the wake from the outbound ferry overlaps the wake pattern from the LNGC and escort tugs.

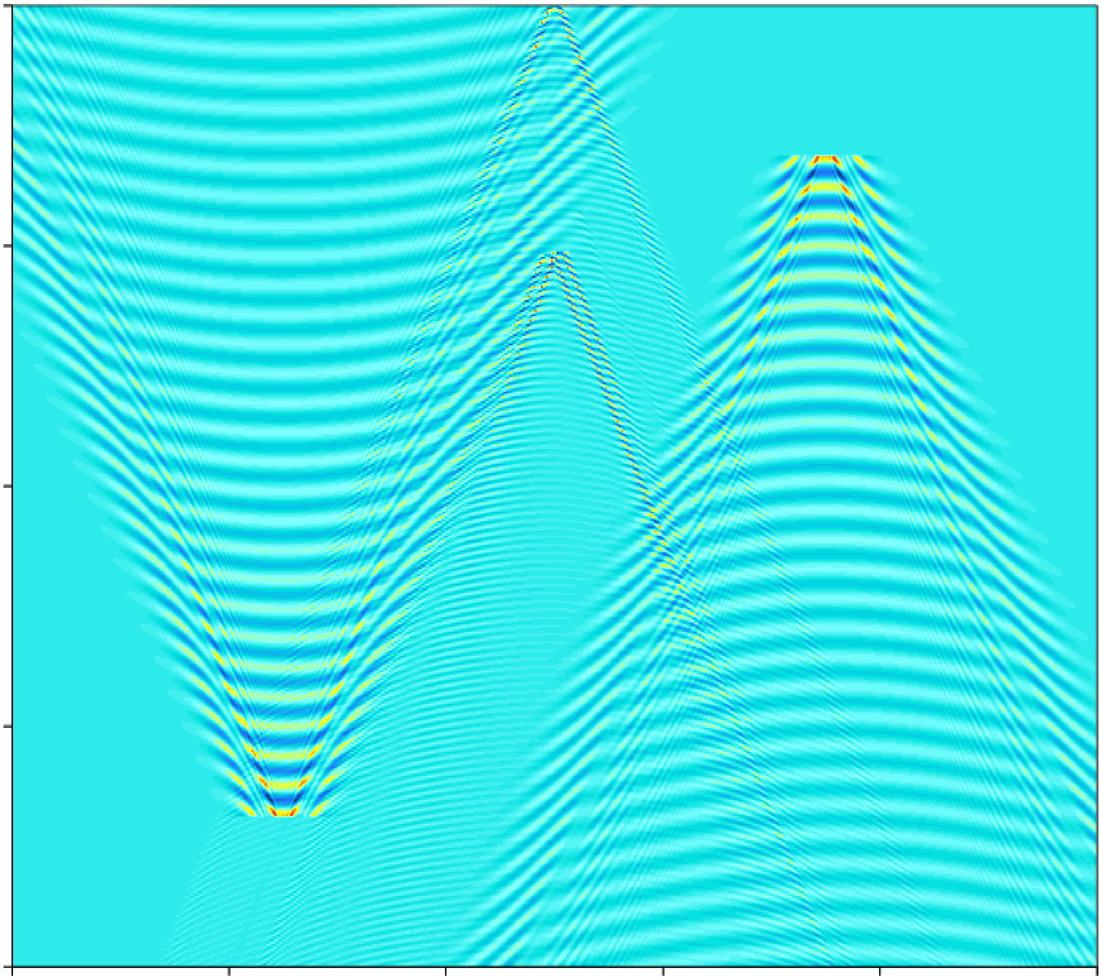


Figure 4-15: Wake computed for LNGC, three escort tugs, and two BC ferries passing over a 2 km × 2 km area.

Figure 4-16 shows a transect of the combined wake pattern of the LNGC, escort tugs and passing ferries approximately center across the middle of Figure 4-15.

The combined water surface elevation reflects a complex interaction of the various wake waves. In order to highlight how each of the vessels contribute to the combined wake pattern, the wakes for individual vessels are indicated by the colored lines with the combined wake indicated by the heavier black line.

The primary conclusion is that the combined wake field presents a rather confused wave field, but it is of interest to note that although the wake patterns overlap, the waves don't necessarily superimpose to form a combined larger wave. This is because the ferries travel at different speeds than the LNGC and escort tugs. The difference in vessel speeds causes the wake patterns of the ferries to propagate at a different speed, while the wake wave lengths are also longer that those produced by the LNGC and escort tugs. The overall effect is that the ferry wakes pass the wakes from the LNGC and tugs and momentarily produces an interference between wave fields, and not necessarily produce a much larger wave height.

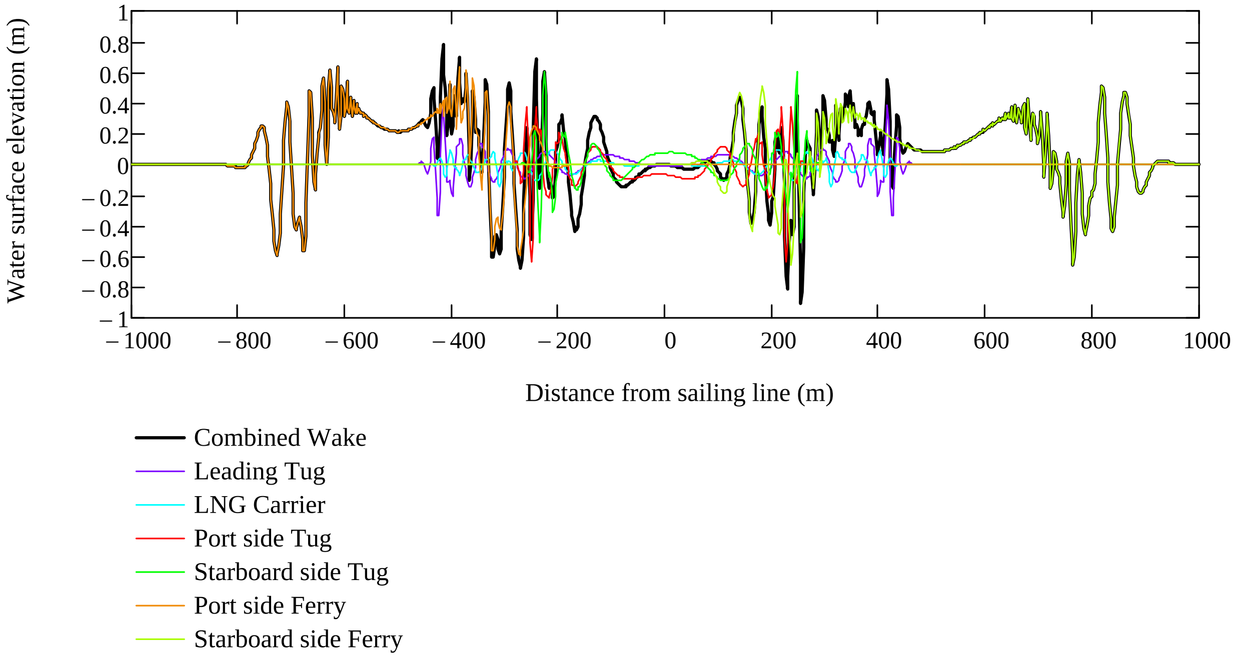


Figure 4-16: Combined wake from LNGC, three escort tugs, and BC ferries passing.

For an observer at the shoreline, the wakes would be seen as arriving separate from one another, e.g. on a shoreline located at the right-hand side of the figure, the ferry wake (light green) would arrive first, followed by the wake from the leading tug (purple line); then the wake from the LNGC (cyan line), and shortly thereafter the wakes from the starboard and port side tugs (green and red lines). The waves arriving at shore would be observable over an estimated period of between 1 and 4 minutes.

4.7 PACIFICAT FAST FERRIES

Figure 4-17 shows a plan view of the wake pattern computed for a PacifiCat fast ferry. Again, the cyan background is representative of the mean sea level. Wave crests of increasing height are indicated in yellow, orange, and red colors. The crests of the very highest of the waves are indicated in white. These are typically seen in the top portion of the figure which is at the stern of the vessel.

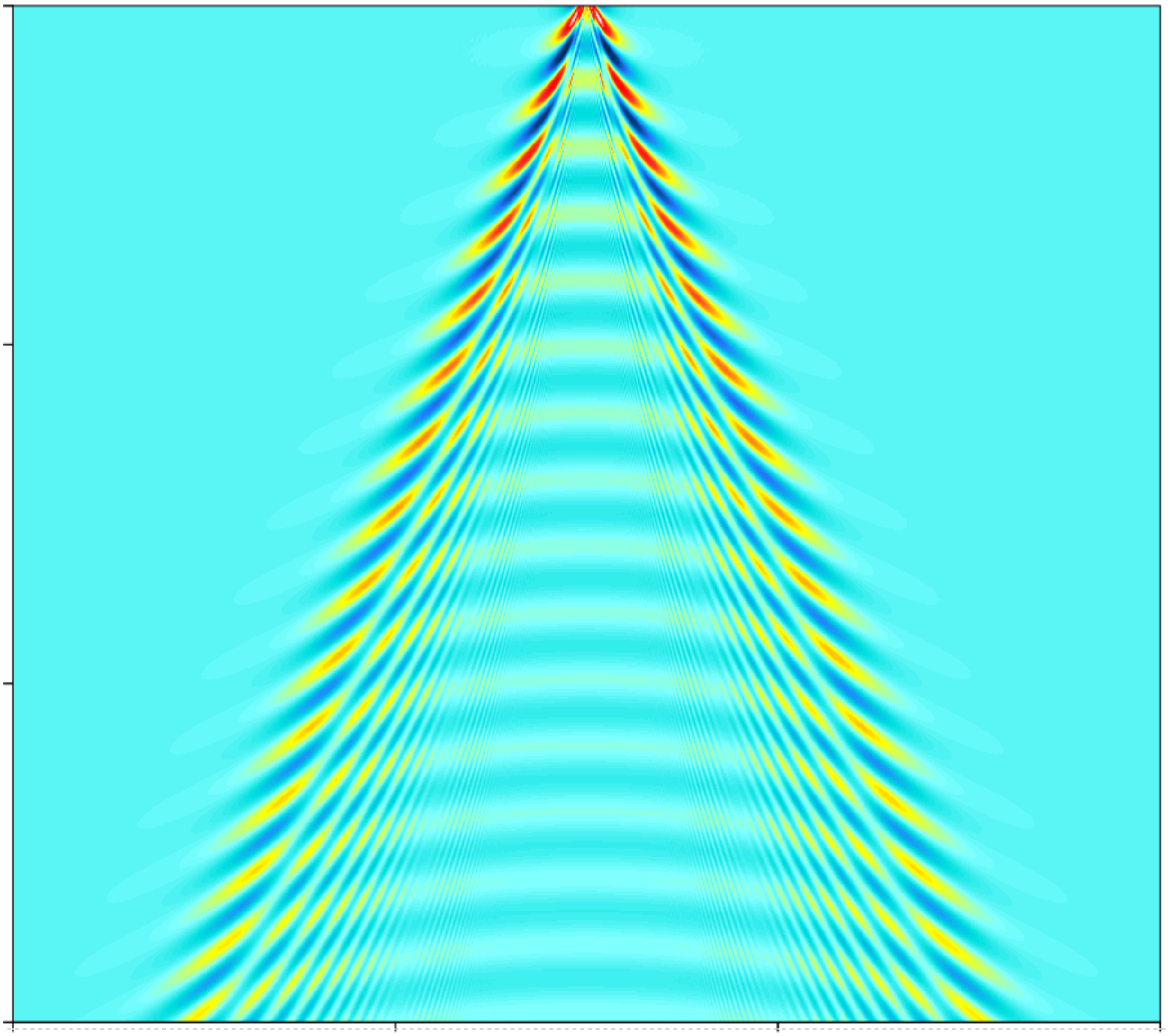


Figure 4-17: Plan view of vessel wake computed for PacifiCat Fast Ferry over a 3 km × 3 km area.

The vessel wake pattern seen in the figure is very pronounced compared to that computed for other vessels (Figure 4-1, Figure 4-3, Figure 4-7, Figure 4-10, Figure 4-13). Most apparent is the fact that the wave lengths of the wake waves are much longer than those computed for tugs, LNGC, and existing BC ferries. This is because the PacifiCat fast ferries were estimated to produce wake waves with periods of around 9 seconds.

It can be seen that the highest wake waves occur immediate aft of the vessel (top of figure) and that the wave heights remain significant over a large area behind the vessel indicated by the red color of the wave crests. The figure supports the fact that wake waves would have been noticeable along the shore in some areas. This is especially true considering the wave period is much longer and the celerity much faster than can occur under natural conditions or from other vessels in Howe Sound. These waves would therefore approach and break on the shore in noticeably different manner than other types of waves. The distance from the sailing line to the wave crests along the bottom of the figure is around 1 km.

Figure 4-18 shows wave transects at distances of 150 m, 1200 m, 1800 m, 2900 m, 3600 m, and 4300 m behind the vessel. The dotted red line gives an indication of the wave height attenuation with distance. Because the PacifiCat fast ferries produced waves with long periods and long wave lengths, the attenuation of the wave height with distance is much less than for the other vessels considered in this analysis.

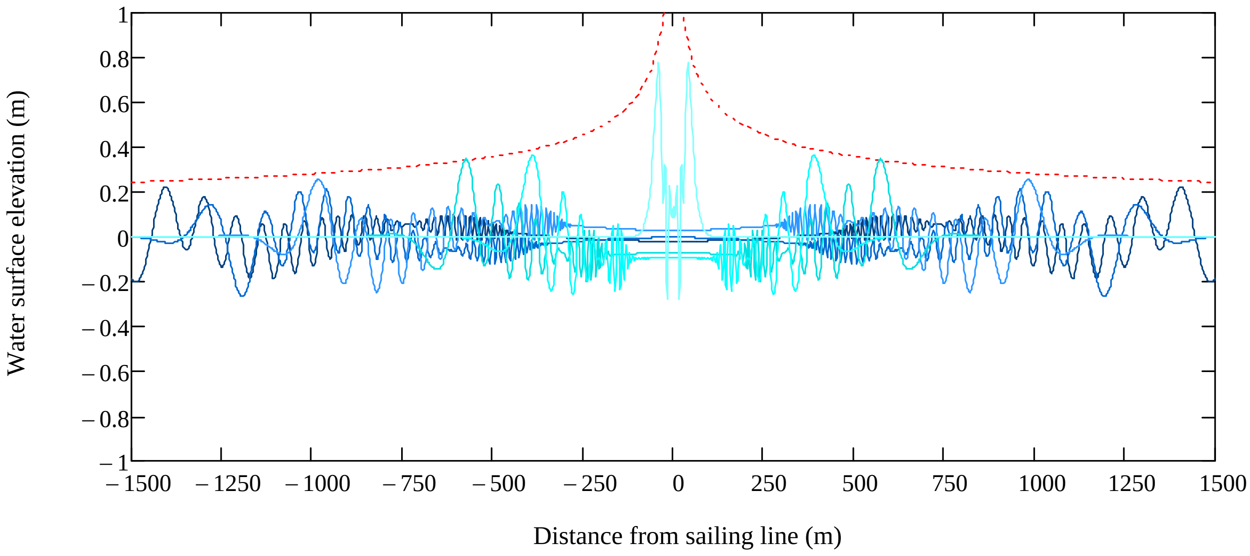


Figure 4-18: PacifiCat fast ferry wake transects.

4.7.1 Comparative Results

For reference *ASL (1999)* conducted extended full scale field trials to study wake characteristics of the PacifiCat fast ferries in deep and shallow water at a range of transit speeds. The study found that at a vessel speed of 34 knots, the primary diverging wave height was 1.0 m near the vessel and the wave period 9 seconds. For the same vessel speed, the secondary diverging wave had a height of 0.3 m with a wave period of about 4 seconds, and the corresponding values for the transverse wake waves were 0.2 m and 11.2 seconds.

Figure 4-19 shows an example of typical wake data acquired during the *ASL (1999)* field trials. In the example, the water depth was around 68.1 m and the maximum wake wave height recorded around (68.50 m – 67.65) = 0.85 m. The ASL field data collection program also included field measurements of C-Class ferries (Queen of Coquitlam and Queen of Alberni) that showed wake heights of 0.4m to 0.5m when the ferries were travelling at speeds of approximately 18-20 knots. Findings of the ASL field data collection and data analysis is summarized in *BCFC (2000)*, and was found to be comparable to the results developed in the present study.

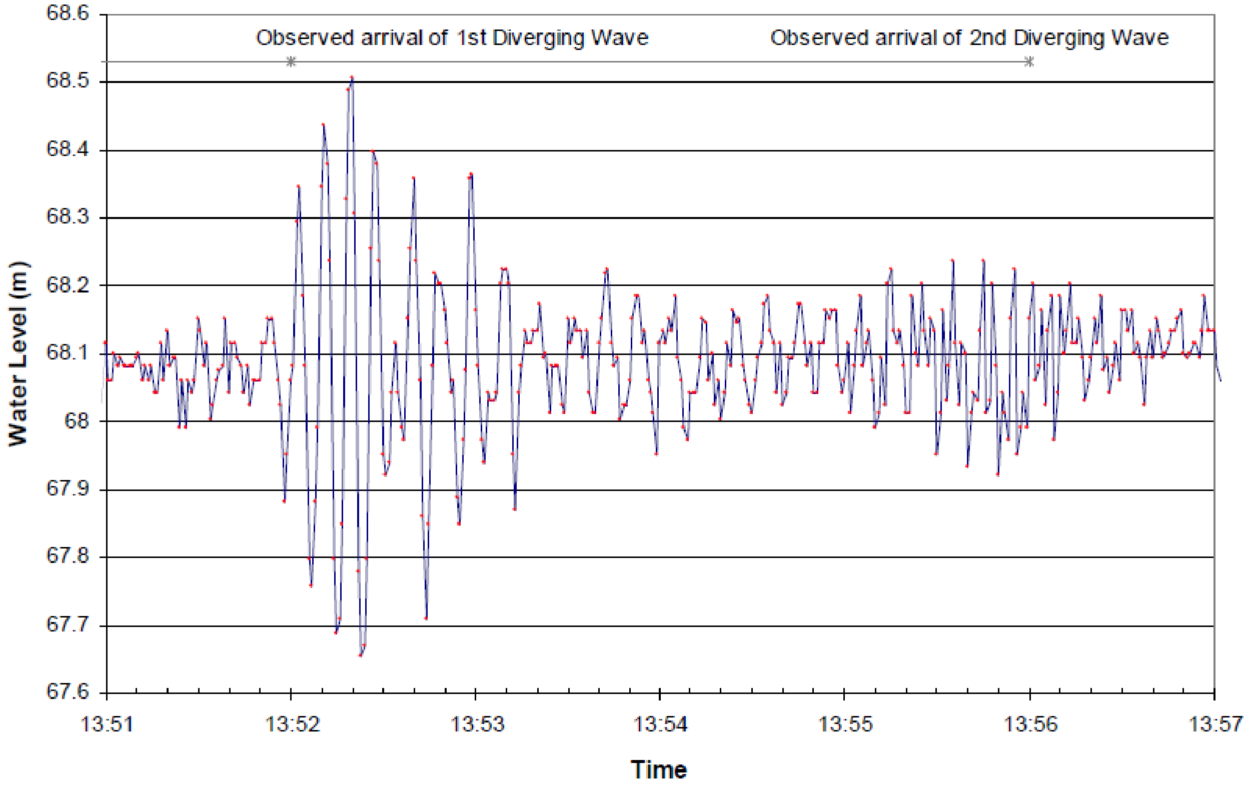


Figure 4-19: Example of typical wake data obtained in field trials. Reproduced from *ASL (1999)*.

5. COMPARISON OF PREDICTED WAKE EFFECTS TO NATURAL WAVES

In the following, the magnitude of wake estimated for the vessels considered is compared to natural waves within Howe Sound.

Figure 2-1 identifies locations of interest along the Woodfibre LNGC route and Table 5-1 summarizes approximate distances to these locations relative to the LNGC sailing line. Most of the locations of interest are at least 1 kilometer away from the Woodfibre LNG sailing route, with the exception of Anvil Island where the closest part of the island is approximately 0.8 km away from the sailing line, assuming the vessel is in mid-channel[6].

---

[6] The shortest distance between the east side of Anvil Island and the eastern shore of Howe Sound near Brunswick Point is approximately 1.6 km.

Based on the theoretical methods (see Chapter 3), *PIANC (1987)* and *Kriebel & Seelig (2005)*, and the Fourier-Kochin representation (see Chapter 4), the secondary vessel waves from the proposed Woodfibre LNG vessels are evaluated in the following. Figure 5-1 through Figure 5-3 illustrate the secondary wave heights with distance away from the sailing line for the LNG carrier, tugs, and worker ferry. Also included are comparative CFD results for a 40-m tug and wake measurements for a fireboat provided by Robert Allan (*Robert Allan, 2015*). In addition, Delft Hydraulics has investigated application of the PIANC method, and determined alternate empirical constants in the case of tugs. These estimates for tugs are included for comparison.

From the adopted methods and resultant figures within this study, none of the vessels transiting to and from the Woodfibre site are expected to generate waves greater than 0.15 meters at the locations considered. Figure 5-4 compares the surface elevation of wake waves to wind waves at the shoreline associated with a typical summer breeze. The typical summer sea breeze conditions were determined to generate a significant wave height (H_s) of 0.18 meters and a peak period (T_p) around 1.5 seconds (see Figure 2-4 and Figure 2-5). As noted above, calculated wakes for vessels within this study are similar in magnitude and period as the natural wind generated waves in the same locations.

Table 5-1: Approximate Distance from the Locations of Interest to LNGC Sailing Line.

Location	Distance to LNGC Sailing Line (km)	Location	Distance to LNGC Sailing Line (km)
Point Atkinson	4.8 km	**Lions Bay**	3.2 km
Bowen Island	2.1 km	**Bowyer Island**	1.0 km
Snug Cove	2.0 km	**Anvil Island**	0.8 km
Whytecliff Park	1.2 km	**Porteau Cove**	2.0 km
Horseshoe Bay	3.1 km	**Britannia Beach**	2.2 km
Langdale	13.4 km	**Woodfibre**	-
Gambier Island	4.0 km	**Squamish**	5.6 km

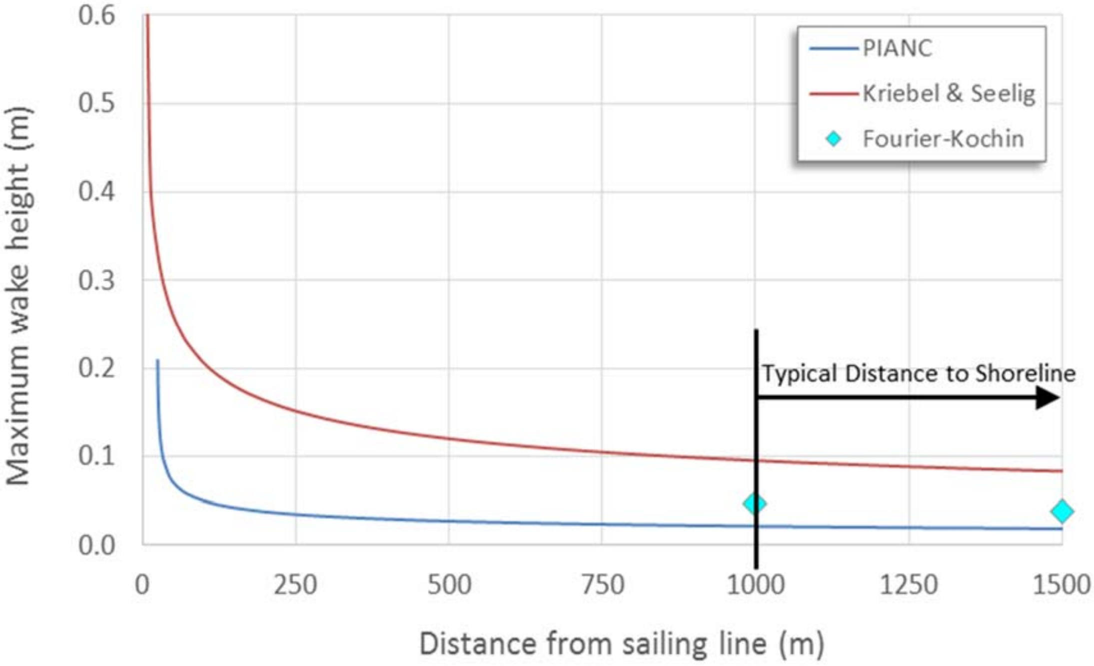


Figure 5-1: Secondary Wave Heights for LNG Carrier away from LNGC Sailing Line.

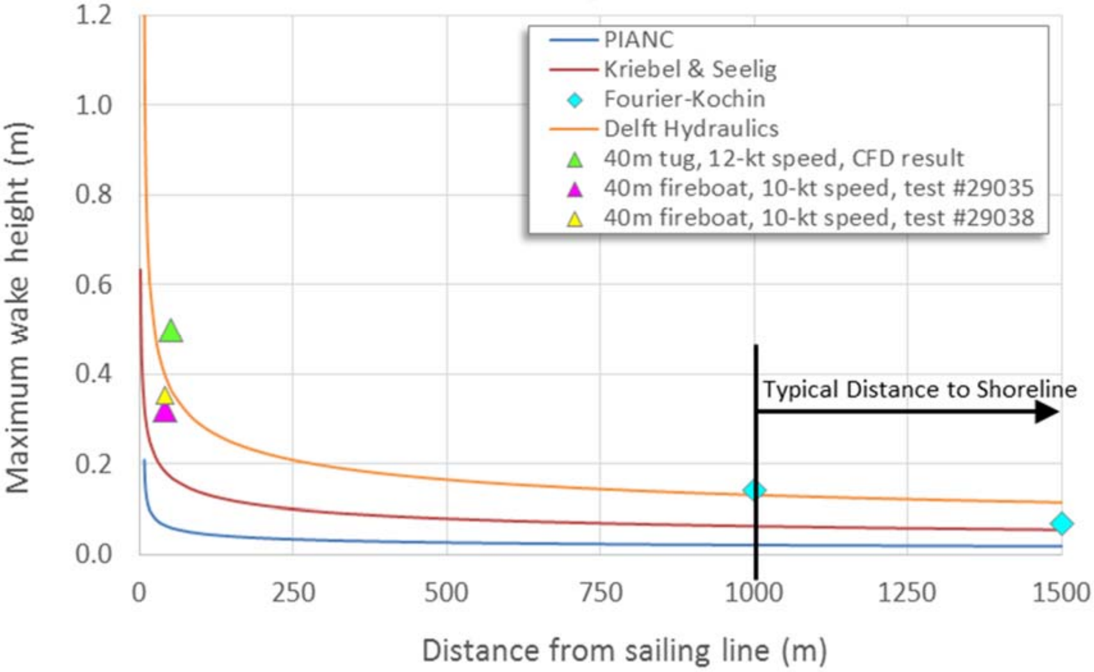


Figure 5-2: Secondary Wave Heights for Tugs away from LNGC Sailing Line.

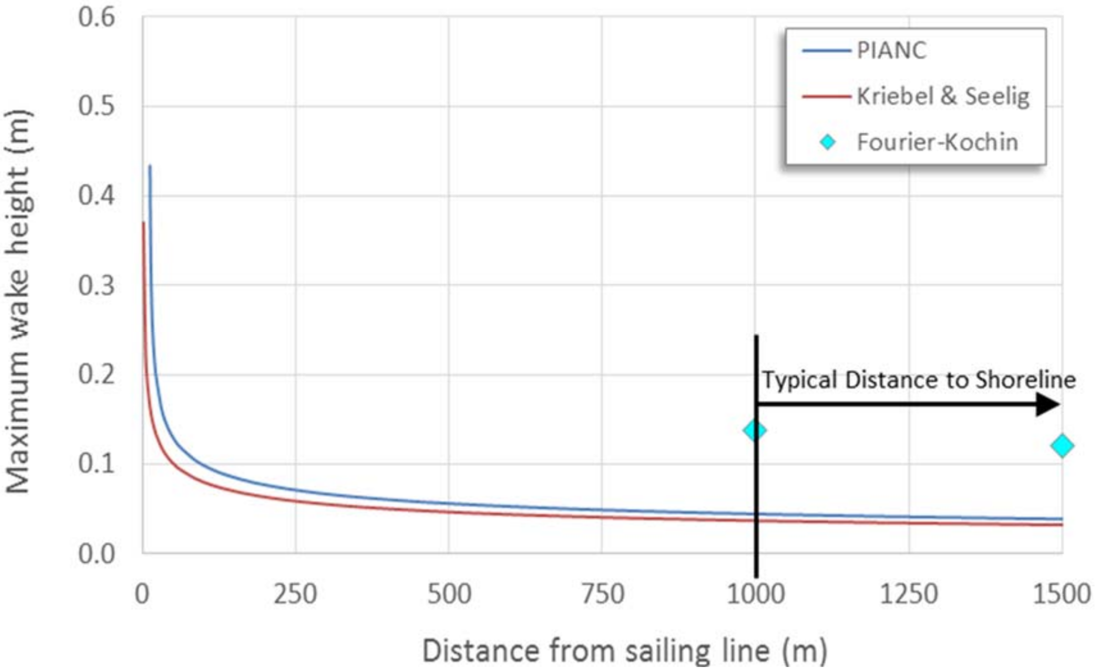


Figure 5-3: Secondary Wave Heights for Worker Ferry away from LNGC Sailing Line.

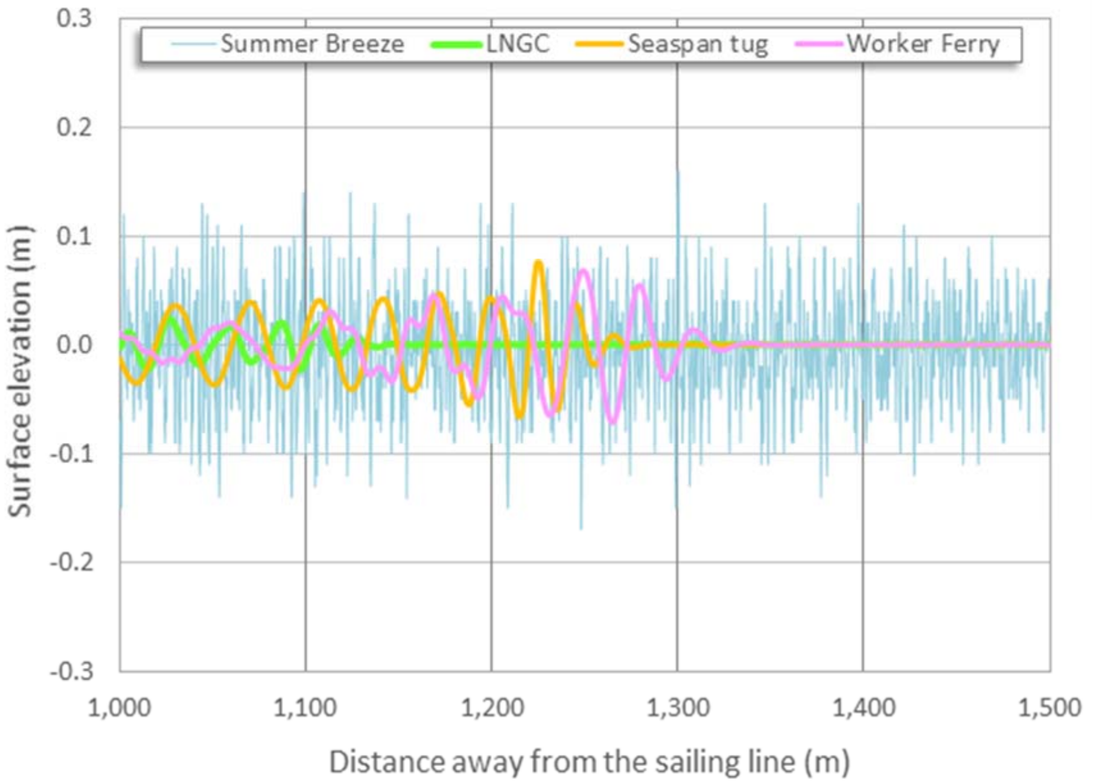


Figure 5-4: Surface Elevation Comparison between Woodfibre Vessels' Secondary Waves and Typical Summer Breeze Wind Waves at 1 to 1.5 km away from LNGC Sailing Line.

6. WAKE WASH IMPACT ON SHORELINES AND INFRASTRUCTURE

Howe Sound is a glacial fjord and predominantly features relatively steep fjord walls and near vertical cliffs. In some locations, more gently sloped beaches comprised of sand, gravel and cobble can be found. Many beaches are isolated “pocket beaches” confined between two relatively steep and rocky headlands, while others are found at creek or river mouths

Typical waterfront infrastructure in Howe Sound includes ferry terminals, marinas, and industrial port facilities (e.g. Squamish). Additional infrastructure near the waterfront is typically associated with access to the water for recreational purposes and may include shoreline parks, floating docks, or boat landings. Common recreational activities include boating and kayaking, wind surfing and kite board surfing, bathing, and scuba diving. The chart of recreational features of Howe Sound in Appendix B provides additional details about recreational boating routes and locations of recreational activity. It is beyond the scope of the present study to evaluate the shoreline within Howe Sound in detail, and thus representative shoreline types and infrastructure are instead considered.

Based on Figure 2-1, a general categorization of waterfront infrastructure at the main locations within Howe Sound has been put together as shown in Table 6-1. The check marks indicate that the particular activity or use is well established or relatively commonplace at those locations. The absence of a check mark is not intended to imply that the activity/use is absent at that location.

Table 6-1: Categorization of Shoreline Infrastructure and Recreational Activities in Howe Sound.

	Infrastructure					Recreational Activities			
Location	Ferry Terminal	Port Facility	Marina	Shoreline Park	Floating Dock or Boat Landing	Boating or Kayaking	Wind/Kite Surfing	Beach (bathing)	Scuba Diving
Point Atkinson				✓					
Bowen Island			✓	✓	✓	✓	✓	✓	✓
Snug Cove	✓		✓	✓	✓	✓		✓	
Whytecliff Park				✓				✓	✓
Horseshoe Bay	✓		✓	✓	✓	✓			
Langdale	✓			✓					
Gambier Island			✓	✓	✓	✓		✓	✓
Lions Bay			✓	✓	✓			✓	✓
Bowyer Island			✓	✓	✓				✓
Anvil Island				✓	✓	✓		✓	
Porteau Cove			✓	✓	✓	✓	✓	✓	✓
Britannia Beach				✓	✓	✓		✓	
Woodfibre					✓				
Squamish		✓	✓	✓	✓	✓	✓	✓	✓

The predominant shoreline types and their interaction with waves can be classified as follows:

- Steep cliff and rocky shore. In general, water is typically fairly deep at such location and the primary wave interaction is reflection. As a rule of thumb, the incident wave height can approximately double at the face of a vertical, reflective shore or structure.
- Rocky or riprapped shore. In general, water depth in front of such structures can range from intermediate to shallow and the primary wave interaction is wave runup, wave breaking, and in some cases wave overtopping. For general guidance, larger waves will typically break against such structures, whereas smaller waves may be subject to an amount of reflection.

- Sandy or gravelly gently sloping shores. The water depth at such shores typically varies very gradually, progressively deepening with distance from shore. The primary modes of wave interaction include wave runup and wave breaking. As a rule of thumb, the waves will be depth-limited meaning that their height does not progress above a fraction of the water depth. Wave heights are typically limited to around 80% of the water depth.
- Existing maritime infrastructure in Howe Sound (e.g. floats, wharves, docks, mooring buoys, seawalls, etc.) are already exposed to ambient waves, currents and tides. The nature of the project-related wakes is no worse (and generally more benign) than existing ambient conditions.

Subject to the suitability and capability of existing infrastructure to contend with prevailing wind and wave conditions including occasional and transient storms, wake effects from project vessels are not expected to exacerbate the conditions on existing infrastructure or require additional mitigations beyond those considered within the study.

6.1 MITIGATION MEASURES

Because the present study finds that potential wakes from LNG carriers, tugs, and project-related worker ferries are small and comparable to natural waves, no mitigative measures are proposed.

7. CONCLUSIONS

1. Wakes from project vessels are found to be comparable to naturally occurring waves within Howe Sound.

2. Project related vessel traffic volumes will be small relative to existing traffic levels and vessel wakes will not appreciably increase the existing vessel wake environment.

3. Wakes from vessels transiting to Woodfibre are projected to be smaller than the wakes generated by the existing BC Ferries because Woodfibre vessels will transit at lower speeds and will travel as far removed from shore as practicable.

4. Wakes from vessels transiting to the Woodfibre site will be less than wakes generated by existing vessels transiting to Squamish Terminals, because Woodfibre vessels will transit at substantially lower speed.

5. To the extent that the present study is accurate, it is not envisaged that wake waves would heighten exposure of the public, contribute to shoreline erosion, or have any appreciable effect on existing infrastructure within Howe Sound.

6. It is concluded that no additional wake mitigation measures are necessary for project-related vessel traffic beyond those considered within this study.

8. REFERENCES

ASL (1999). D. Fissel, D. Billenness, D. Lemon, and J. Readshaw. *Measurement of the Wave Wash Generated by Fast Ferries with Upward Looking Sonar Instrumentation.* ASL Environmental Sciences Inc. and Sandwell Engineering Inc. Presented at Fast Ferries 2001 Conference, New Orleans.

BCF (2015). BCFerries. www.bcferries.com.

BCFC (2000). *Fast Ferry Program – Wake and Wash Project,* (excerpts of). Developed by Sandwell for the British Columbia Ferry Corporation. Final Report, August 2000.

CEM (2006). *Coastal Engineering Manual.* Engineer Manual EM 1110-2-1100 (Part II), Chapter 7 Harbor Hydrodynamics. U.S. Army Corps of Engineers, 1 June 2006 (Change 1).

DFO (2012). *Sailing Directions – Juan de Fuca Strait and Strait of Georgia*. PAC 201. First Edition. April 2012.

DHI (2012). *Wake Waves at Kitkiata Inlet and Principe Channel. Numerical Wave Transformation Modeling.* Enbridge Northern Gateway Project, British Columbia, Canada. Prepared by DHI for Force Technology. Project No. 11812716, 13 July 2012.

Kriebel, D.L. and Seelig, W.N. (2005). *An Empirical Model for Ship-Generated Waves*. Proceedings of the Fifth International Symposium on Ocean Wave Measurement and Analysis. 2005.

M&N (2015). Woodfibre LNG Project FEED Metocean Analysis. Prepared by Moffatt & Nichol for Woodfibre LNG Limited. M&N Project No. 8359-02. January 29, 2015.

PIANC (1987). *Guidelines for the design and construction of flexible revetments incorporating geotextiles for inland waterways.* PIANC, Permanent International Association of Navigation Congresses. Report of Working Group 4 of the Permanent Technical Committee I. Supplement to Bulletin N° 57 (1987). General Secretariat of PIANC, Résidence Palace, rue de la Loi 155, B. 9, 1040 Brussels (Belgium).

Revathi et al. (2012). C. Revathi, and M.K. Khan. *Theoretical Ship Wave Pattern Resistance Evaluation Using Kochin Wave Amplitude Function.* International Journal of Innovative Research & Development. ISSN: 2278-0211 (Online). Vol. 1, Issue 10 (Special Issue). www.ijird.com. December, 2012.

Robert Allan Ltd. (2015). Personal Communication. April 15, 2015.

Schierech, G.J. (2001). *Introduction to Bed, Bank and Shore Protection*. Delft University Press. 2001.

Tuck et al. (2001). E.O. Tuck, D.C. Scullen and L. Lazauskas. D.C., *Ship-Wave Patterns in the Spirit of Michell.* IUTAM Symposium on Free Surface Flows. Fluid Mechanics and Its Applications, Volume 62, 2001, pp 311-318.

Tuck (2003). E.O. Tuck. *Computation and Minimisation of Ship Waves*, in Applied Mathematics Entering the 21st Century. Invited Talks from the ICIAM 2003 Congress. Edited by: James M. Hill, University of Wollongong, New South Wales. Edited by: Ross Moore, Macquarie University, Sydney. ISBN: 9780898715590. Academic and Professional Books. Cambridge University Press.

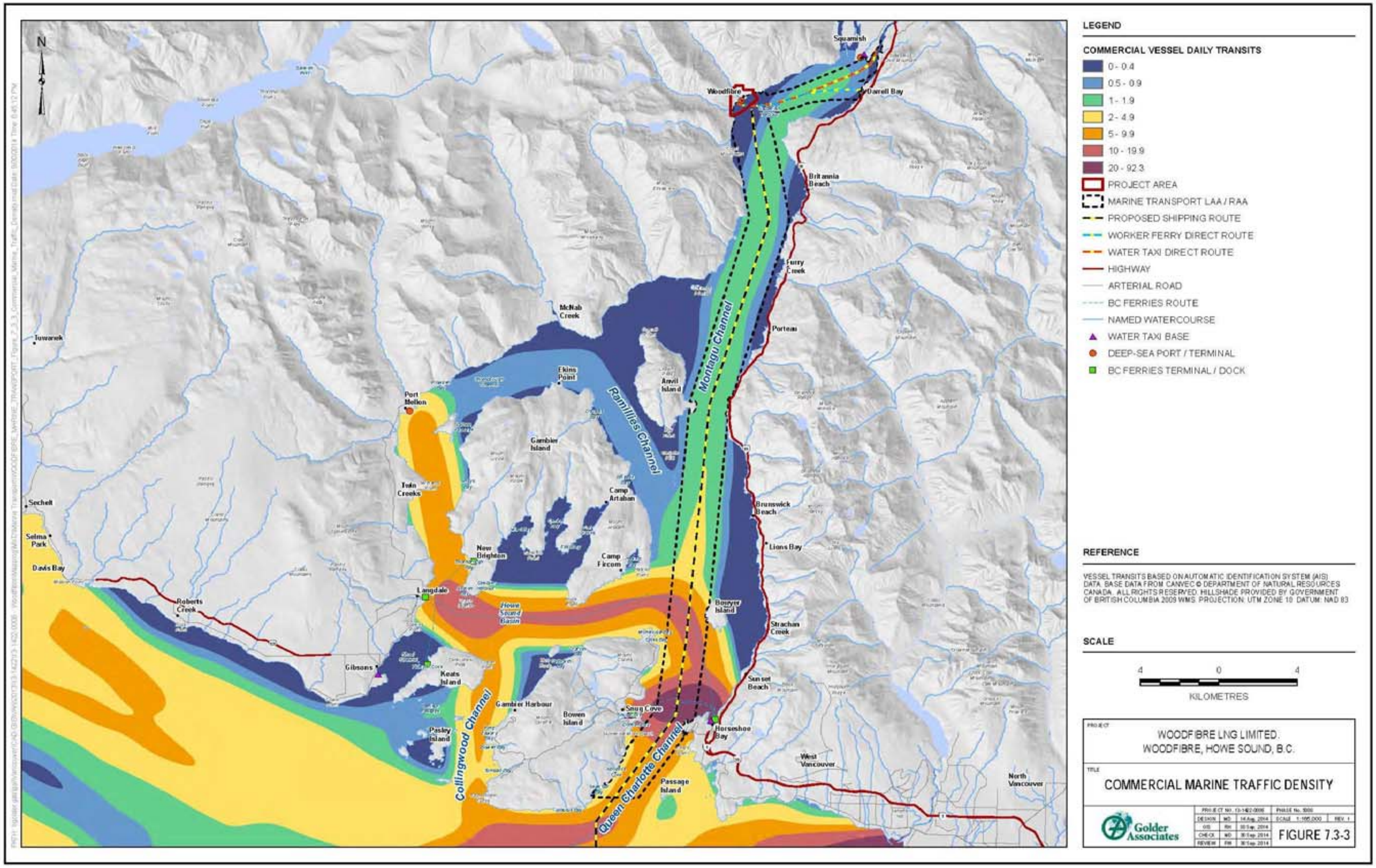
Verhey et al. (1989). H.J. Verhey and M.P. Bogaerts. *Ship waves and the stability of armour layers protecting slopes.* Delft Publication number 428. Delft Hydraulics, November 1989.

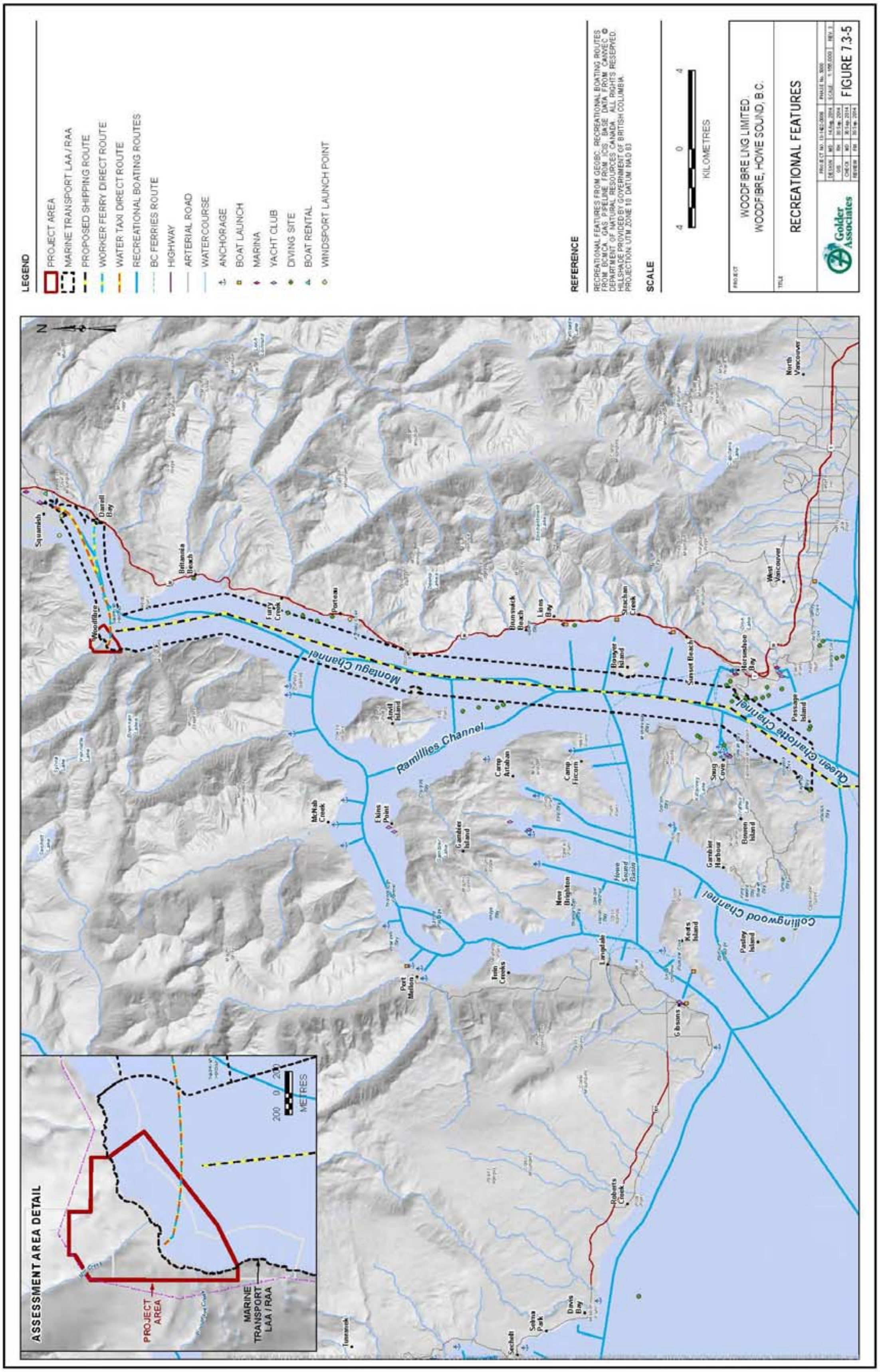
WebArchive (2015). *PacifiCat Fast Ferries.*
http://web.archive.org/web/20010406150051/http://www.pacificat.com/specs.htm

Wikipedia (2015). *High speed ferries.* www.wikipedia.org.

Appendix A – Howe Sound Marine Traffic and Recreational Features

Charts of commercial marine traffic density and recreational features of Howe Sound, B.C. developed by Golder Associates Ltd.


N
Squamish
Woodfibre
Darrell Bay
Britannia Beach
Furry Creek
Porteau
McNab Creek
Montagu Channel
Anvil Island
Ramillies Channel
Ekins Point
Port Mellon
Gambier Island
Twin Creeks
Camp Artaban
Brunswick Beach
Lions Bay
New Brighton
Camp Fircom
Langdale
Howe Sound Basin
Bowyer Island
Strachan Creek
Sechelt
Selma Park
Davis Bay
Roberts Creek
Gibsons
Keats Island
Gambier Harbour
Bowen Island
Snug Cove
Sunset Beach
Horseshoe Bay
Pasley Island
Collingwood Channel
Queen Charlotte Channel
Passage Island
West Vancouver
North Vancouver
Tuwanek
LEGEND
COMMERCIAL VESSEL DAILY TRANSITS
0 - 0.4
0.5 - 0.9
1 - 1.9
2 - 4.9
5 - 9.9
10 - 19.9
20 - 92.3
PROJECT AREA
MARINE TRANSPORT LAA / RAA
PROPOSED SHIPPING ROUTE
WORKER FERRY DIRECT ROUTE
WATER TAXI DIRECT ROUTE
HIGHWAY
ARTERIAL ROAD
BC FERRIES ROUTE
NAMED WATERCOURSE
WATER TAXI BASE
DEEP-SEA PORT / TERMINAL
BC FERRIES TERMINAL / DOCK
REFERENCE
VESSEL TRANSITS BASED ON AUTOMATIC IDENTIFICATION SYSTEM (AIS) DATA. BASE DATA FROM CANVEC © DEPARTMENT OF NATURAL RESOURCES CANADA. ALL RIGHTS RESERVED. HILLSHADE PROVIDED BY GOVERNMENT OF BRITISH COLUMBIA 2009 WMS. PROJECTION: UTM ZONE 10 DATUM: NAD 83
SCALE
4
0
4
KILOMETRES
PROJECT
WOODFIBRE LNG LIMITED.
WOODFIBRE, HOWE SOUND, B.C.
TITLE
COMMERCIAL MARINE TRAFFIC DENSITY
Golder Associates
PROJECT No. 13-1422-0006
PHASE No. 5000
DESIGN MD 14 Aug. 2014
SCALE 1:165,000
REV. 1
GIS RH 30 Sep. 2014
CHECK MD 30 Sep. 2014
REVIEW FW 30 Sep. 2014
FIGURE 7.3-3


LEGEND
PROJECT AREA
MARINE TRANSPORT LAA / RAA
PROPOSED SHIPPING ROUTE
WORKER FERRY DIRECT ROUTE
WATER TAXI DIRECT ROUTE
RECREATIONAL BOATING ROUTES
BC FERRIES ROUTE
HIGHWAY
ARTERIAL ROAD
WATERCOURSE
ANCHORAGE
BOAT LAUNCH
MARINA
YACHT CLUB
DIVING SITE
BOAT RENTAL
WINDSPORT LAUNCH POINT
REFERENCE
RECREATIONAL FEATURES FROM GEOBC. RECREATIONAL BOATING ROUTES FROM BCMCA. GAS PIPELINE FROM IOS. BASE DATA FROM CANVEC © DEPARTMENT OF NATURAL RESOURCES CANADA. ALL RIGHTS RESERVED. HILLSHADE PROVIDED BY GOVERNMENT OF BRITISH COLUMBIA. PROJECTION: UTM ZONE 10 DATUM: NAD 83
SCALE
4
0
4
KILOMETRES
PROJECT
WOODFIBRE LNG LIMITED
WOODFIBRE, HOWE SOUND, B.C.
TITLE
RECREATIONAL FEATURES
Golder Associates
FIGURE 7.3-5
ASSESSMENT AREA DETAIL
PROJECT AREA
MARINE TRANSPORT LAA / RAA
200
0
200
METRES
Squamish
Darrell Bay
Woodfibre
Britannia Beach
Furry Creek
Porteau
Brunswick Beach
Lions Bay
Strachan Creek
Bowyer Island
Sunset Beach
Horseshoe Bay
West Vancouver
North Vancouver
Passage Island
Montagu Channel
Anvil Island
Ramillies Channel
Queen Charlotte Channel
Camp Artaban
Camp Fircom
Snug Cove
Bowen Island
McNab Creek
Ekins Point
Gambier Island
Gambier Harbour
New Brighton
Howe Sound Basin
Collingwood Channel
Keats Island
Pasley Island
Port Mellon
Twin Creeks
Langdale
Gibsons
Roberts Creek
Davis Bay
Selma Park
Sechelt
Tuwanek

Appendix B – Vessel Wake Commentary

Commentary and examples of wake from vessels comparable to those considered in the study are provided in the following.

WAKES GENERATED BY LNG CARRIERS

In the following, excerpts of footage of LNGC Stena Clear Sky at sea are provided (Source: www.youtube.com/watch?v=vms-9dnJJKY).

From certain angles the vessel wake is visible Figure B-1. As guidance to vertical scale in the images, the height of the hull is around 14 meters from the water line to the deck.

In other views (Figure B-2, Figure B-3, Figure B-4) the wake is not noticeable relative to the sea state.

Figure B-1: Wake pattern observed in footage of Stena Clear Sky LNGC.

Figure B-2: View of Stena Clear Sky LNGC (wide angle).

Figure B-3: View of Stena Clear Sky LNGC (stern).

Figure B-4: View of Stena Clear Sky LNGC (bow).

WAKES ASSOCIATED WITH ESCORT TUGS

Figure B-5 provides an example of a LNGC with tug escort (Source: LNG World News. http://www.lngworldnews.com/wp-content/uploads/2012/01/Stena-Considers-Ordering-Five-LNG-Tankers.jpg).

The tugs are not whole captured in the image, but one tug is tethered forward of the vessel indicated by the towline angled down on the right-hand side of the figure. Another tug tethered aft can be seen on the left side of the figure.

A wake pattern in the form of a V-shape is visible from the tug forward of the LNGC. The wake pattern from the LNGC is barely discernible apart from diminutive waves at the stern of the vessel.

Figure B-5: Stena Blue Sky LNGC with tug escort.

WAKES GENERATED BY TUGS

Figure B-6 and Figure B-7 provide examples of Seaspan tugs in service. Figure B-6 shows wake formation alongside at tug at speed. For a sense of scale, the wake wave height can be compared relative to the person on deck.

Figure B-7 shows wake behind a tug towing barges. The wake from the tug is noticeable but at some distance from the tug not discernible from the natural sea state.

Figure B-6: Wake from Seaspan tug. Source: *Flickr (2015)*.

Figure B-7: Seaspan tug. Source: *Seaspan (2015)*.

WAKES GENERATED BY EXISTING BC FERRIES

Examples of wake from existing BC Ferries captured in aerial imagery are provided in Figure B-8, Figure B-9, Figure B-10). The specific vessels have not been determined and transit speeds are not known.

It should also be noted that ferry transits have been captured in aerial photography at several locations along the BC ferry routes and not all cases show evidence of wake formation, likely because the resolution of the imagery is insufficient to capture the wake, or the vessels at the time and speed did not produce a noticeable wake.

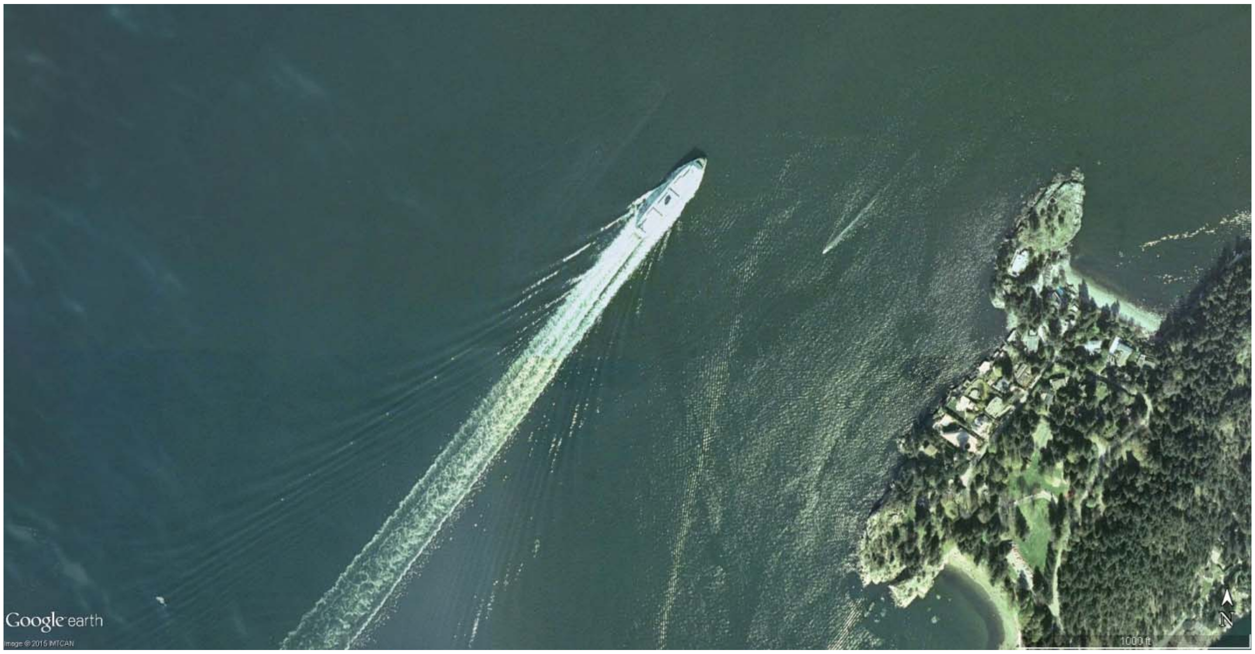


Figure B-8: Wake from BC Ferry approaching Horseshoe Bay (Source: *GoogleEarth 3/20/2004*).

Figure B-9: Wake from BC Ferry arriving at Horseshoe Bay (Source: *GoogleEarth 8/24/2003*).

Figure B-10: Wake from BC Ferry departing Horseshoe Bay (Source: *GoogleEarth 8/29/2003*).

WAKES GENERATED BY PACIFICAT FAST FERRIES

An example of the wake produced by one of the PacifiCat fast ferries is shown in Figure B-11.

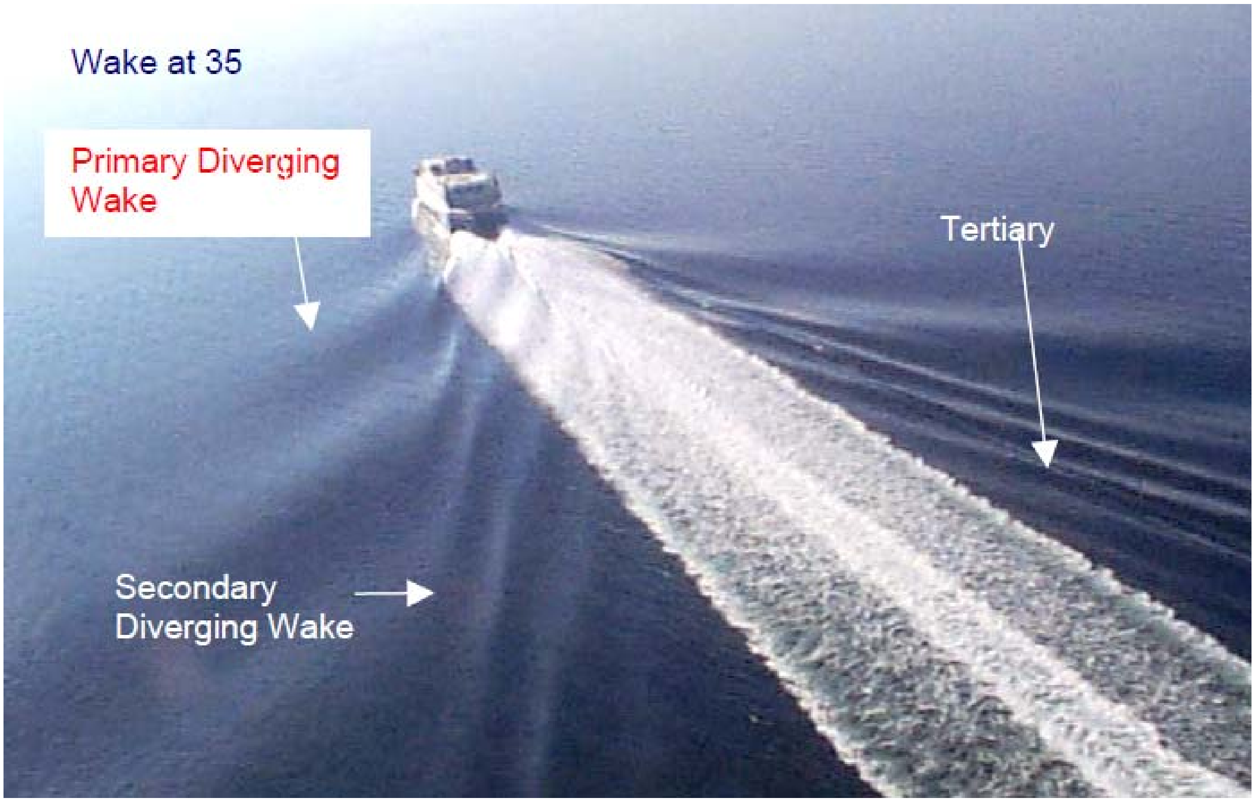


Figure B-11: Wake produced by PacifiCat Fast Ferry. *Source: ASL (1999).*